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Journal of Sedimentary Petrology

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A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

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Journal of Sedimentary Petrology

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NOTICE

Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal*, should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 13, NO. 3, PP. 85–104
FIGS. 1–4, TABLES 1–8, DECEMBER, 1943

RAPID METHODS OF MAKING SEDIMENTATIONAL ANALYSES OF ARENACEOUS SEDIMENTS*

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ABSTRACT

In an attempt to analyze some strongly cemented sandstones, it was found that the standard sedimentational methods of analysis could not be used. New methods have been developed using the projected image of the sandstone grains for determinations of size, shape, and roundness. It is shown that a very small number of grains, usually less than 50, can be used to give all the parameters of the grain distribution with sufficient accuracy for most purposes. Certain other short-cuts and methods of analysis are also presented.

INTRODUCTION

In a recent investigation of Bethel sandstone cores taken from oil wells drilled in south-central Illinois, it was found that the usual sedimentational procedures had to be extensively revised on account of the hard siliceous cement which prevented breaking down the sandstone cores into their component sand grains.

Some of the more loosely cemented cores could be disaggregated, but the majority either resisted all mechanical attempts or yielded large quantities of aggregates and cross-fractured grains.

Chemical treatment likewise failed, although fragments of the core were leached in hydrochloric acid, treated with potassium hydroxide, or boiled in concentrated sodium carbonate and then plunged into hydrochloric acid in the hope that the carbon dioxide thus generated might break the grains loose.

* Published with the permission of the Chief, Illinois State Geological Survey. This report is part of a thesis on "The Bethel Sandstone of South-Central Illinois," submitted in partial fulfillment of requirements for the degree of Doctor of Philosophy at the University of Chicago. The author wishes to acknowledge the kind cooperation of the Illinois State Geological Survey, which organization made this study possible. Special acknowledgment is made of the interest taken in the investigation by Dr. T. Gillette and Mr. L. E. Workman of the Survey, and the interest and assistance of the faculty of the Department of Geology of the University of Chicago where the research work was carried out.

One of the most effective methods of disaggregation consisted in using a solution of photographic "hypo" (sodium thiosulphate). During part of the experimental work the solution was so concentrated that upon cooling it became a solid crystalline mass. Core fragments were placed in the solution which was heated until all the "hypo" crystals had gone into solution. Upon cooling, the force of their crystallization was sufficient to partly disaggregate the core. Repeated solution and crystallization of the "hypo" by alternately heating and cooling aided the disintegration. It was found that a more effective, though slower, method consisted in partly immersing a fragment of the core in a dilute solution of cold "hypo." As the "hypo" solution was drawn up into the core and evaporated at the surface, the "hypo" crystallized in the pores and disaggregated the upper part of the core. However, these "hypo" methods are too slow except for certain special cases.

The conclusion of these preliminary studies was that it would be impractical to attempt to run satisfactory analyses of the Bethel sandstone cores by the ordinary sieving methods because of the difficulty of obtaining satisfactory disaggregation.

Projection Method

The projection method used to determine size distribution depends upon a numerical-frequency distribution of the

properties of grains in a sample. This differs from sieving methods which depend upon the weight of material retained upon each sieve to give a weight-size-frequency distribution of the grains in the sample.

Instruments

A representative number of grains is mounted upon a glass slide and their image is projected upon a screen. The intermediate diameter of the grains, which is usually identical with their short diameter as they lie upon the slide, is measured. This diameter is used to classify the grains into certain size groups which correspond to the groups that would be retained upon a selected series of sieves.

The projector[1] used in this work is essentially an inverted microscope mounted on a tripod. A bulb yielding a point source of light furnishes the illumination. The light passes vertically downward through a weak lens system and then through the slide, which rests upon a rotating stage with an opening in the center. A condenser can be inserted if a greater light intensity is needed. Below the stage is a collar to which objectives of any power can be attached, thus permitting a wide range in magnification. When higher magnifications are desired than are obtainable by the use of simple objectives, a microscope tube is attached to the collar of one of the objectives and increased magnifications are secured by using oculars of different magnifications. With the microscope tube attached, the instrument is an ordinary compound microscope except that the stage is inverted better to accommodate the slide. Projection is vertically downward on a white table-top.

Preparation of Sample for Study

Selecting and cleaning grains.—The actual procedure consists of selecting a core, cracking it open so as to secure a fresh surface perpendicular to the bedding, and brushing off about a thousand grains with a stiff wire brush into a large glazed porcelain evaporating dish. By properly holding the brush, grains can be taken from either the whole section of the core or from a single lens in it.

Grains to be studied may be either mounted directly if they are "clean," or they may be first treated with hydrochloric acid to remove carbonate and iron, or with carbon tetrachloride, acetone, or other solvents to remove excessive oil. Where strong cleaning treatment is necessary, the grains are first placed on a slide which has a hollow ground into it.[2] Grains in the depression can be chemically treated as in a crucible. When heat treatment is necessary, the writer usually places the slide on the top of his microscope light and while he is examining one slide the first one will be heated enough for all reactions to take place. If higher temperatures are needed, the slide may be placed over an electric resistance or hot plate. Liquid is either removed by using a medicine dropper or by means of capillary tubes as in ordinary microchemical analysis. Grains should always be washed and dried before mounting them in index oils.

After treatment, the grains are either transferred to another slide and mounted or the depression is filled with mounting fluid; a cover-glass is laid over the depression and the grains are projected.

Mounting.—A fine camel's-hair brush is used to gather the grains in the porcelain evaporating dish into a pile and then they are swept out through the lip

[1] This projector was the "Promer Microscopic drawing and projection apparatus" for sale by the Clay-Adams Company, New York, N. Y.

[2] If such slides are not available, an ordinary slide may be converted by simply laying it across a metal plate through which a hole slightly smaller than the width of the slide has been drilled. Upon careful heating, a depression in the center of the slide will result when it is brought to a sufficiently high temperature for the glass to sag in the unsupported portion over the hole. To make the slide lie level, the ends may be built up with cardboard or some other material.

of the dish into either a funnel or directly onto a slide. An ordinary glass funnel is satisfactory but more convenient is a short stemmed miniature one about half an inch in diameter. The funnel can be supported over the slide by a tripod which can be made of brass, but equally good is one made of a single-holed stopper which has four match sticks driven into the sides for legs. The funnel is inserted in the hole so that the stem clears the slide by about a quarter of an inch. It may be convenient to have a simple cylinder of glass about a quarter of an inch deep and three quarters of an inch in diameter—such as may be made by cutting off a portion of a shell vial—to place on the slide around the stem of the funnel. This will prevent the grains from rolling or bouncing off the slide as they fall upon its surface. The device is shown in Figure 1. A similar instrument consisting essentially of a brass cylinder, which has had a conical hopper drilled in each end so that the vertices intersect, can be set directly on the slide. The grains are poured into the upper hopper; the lower inverted conical hopper permits the grains to spread out.[3]

For effective study and rapid size determination, the grains must be mounted so that their outlines are readily visible. Quartz has indices of refraction slightly over 1.54; grains mounted in clove oil (index 1.54) show but indistinct outlines. The other extreme is to mount the grains in air. This gives very high relief, in fact, so high that details of outline are lacking. Grains should be mounted in liquids of index of refraction either considerably higher or lower than the index of the grains being studied. Liquids of low index of refraction are preferable to those of high index because few grains have indices much lower than 1.54. Water (index 1.33) was used in early studies but this was found unsatisfactory owing to its rapid evaporation under the heat of the projector light. Later, glycerine (index 1.47) was used but outlines of quartz were somewhat faint. However, glycerine and water are completely miscible and it was found that a mixture of one-third glycerine and two-thirds water was satisfactory, cheap and readily prepared. The water lowers the index of the glycerine sufficiently to yield sharp outlines of the grains and the glycerine retards the evaporation of the water so that the slide will remain intact for a number of hours and sometimes for days.

[3] This constitutes the essential portion of a mounting device designed by G. H. Otto.

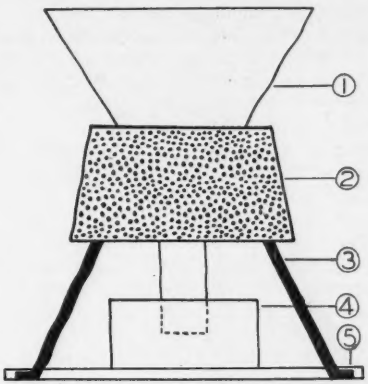


FIG. 1.—Sand grain mounting device. A short funnel (1) passes through a stopper (2) which is supported by four legs (3) spread so as to straddle the glass slide (5) upon which the sand grains are mounted. A retaining ring (4) prevents the grains from bouncing off the slide.

All grains are first mounted in acetone. This accomplishes two purposes: (1) it cleans the grains of oil residue so that they can be completely wetted by the mounting medium; (2) it eliminates air bubbles. The procedure is as follows: Several drops of acetone are put on a slide and the grains are placed in these drops. The grains are then covered with a cover-glass and more acetone is added until the area under the glass is entirely filled with acetone. Then drops of the water-glycerine mixture are gradually added to one edge of the cover-glass. As

the acetone evaporates at one side of the cover-glass, drops of the water-glycerine mixture are added to the opposite side and are uniformly drawn under the cover-glass. This method of mounting wets the sand grains uniformly with the index fluid and eliminates all air bubbles. A further advantage of the use of glycerine rather than other mounting oils is that it is readily soluble in water and permits very easy cleaning of all cover-glasses and slides.

To test the validity of determinations when the mounting media used have indices of refraction considerably different from the grains, several tests were run upon grains mounted in clove oil (index 1.54), glycerine (index 1.47), water-glycerine mixture (index 1.38), and air (index 1.00), to compare the results. In studying the grains mounted in clove oil, the projector was equipped with two polaroids to aid in delimiting the grain boundaries. These polaroids could be rotated allowing the projector stage to remain undisturbed. No essential difference was found between the determinations of size, shape and roundness of the grains except that the lack of sharp and distinct outlines increased errors as the difference between the indices of the mounting medium and grains decreased. Between the clove oil or water-glycerine mounts and the air mounts the size and shape determinations were not markedly different, but there was a considerable difference in the roundness determination owing to loss of detail and fuzzy outlines given by the air mount. This loss of detail made the grains appear rounder than they actually were. As a result the water-glycerine mixture was used because it yielded valid results, good grain outlines, ease of preparation and ease of cleaning slides.

Magnification.—Any magnification may be used but one of a hundred times is most convenient because of the ease of converting the measurements to their true size. However, when grains are very coarse, a magnification of fifty times may be more suitable.

Treatment of grain outlines.—It is much more convenient to project the grains vertically downward upon a white table-top than against a wall or screen. The images of the grains can then be studied directly without tracing the outline on paper as is the common practice in most roundness and shape analyses. A representative area in the projected field is chosen and the grain images are checked off as they are studied. This method saves a great deal of time otherwise lost in tracing the grain outlines.

Size Analysis Methods

If grains are spread out upon a slide, normally they will come to rest on their longest and intermediate diameters with their shortest diameters vertical. As a result, when viewed in the projection, the maximum diameter of the grain outline corresponds with the maximum diameter of the sand grain; the minimum diameter of the projection with the intermediate diameter of the grain.[4]

The "short diameter" is first determined. This diameter is defined as the maximum width of the grain. It could also be defined as the diameter of the opening in a screen which would permit the grain to just pass through. The "long diameter" is equivalent to the longest measurement of the grain taken approximately at right angles to the "short diameter." The "short" and "long" diameters rarely bisect each other.

In sieving procedures, except for very elongate grains, the intermediate diameter is the grain measurement which determines upon which sieve the grain will be caught. Since the intermediate diameter of the grain corresponds to the "short diameter" of the grain projection, it follows that a measure of the "short diameter" of the projected grain gives a means of correlating the two methods of analysis. Class limits were selected which

[4] In this paper the "short diameter" will refer to the short diameter of the projected grain or the intermediate diameter of the actual grain unless otherwise stated.

corresponded to the class limits used in sieving. Thus grains which in sieving would be caught between the ¼–½ mm. sieves will project as grains which have their projected "short diameters" between 12.5 and 50.0 mm. for one hundred magnifications.[5] Table 1 gives the class limits for fifty and one hundred magnifications and the phi unit equivalents.

noting which circle was just larger than the "short diameter" of the projected image. However, this was found to be much more difficult than using a millimeter rule and measuring the actual diameter especially since the "short diameter" is essential in shape determinations. After they are measured, the grains are tabulated according to their size groups,

TABLE 1.—*Limits used for projection grade scale and phi equivalents*

Sieve Opening or Equivalents of Phi Sizes (mm.)	Projection		Phi Class Intervals*	Wentworth Size Classification
	50 Magnifications (mm.)	100 Magnifications (mm.)		
1.000–0.707	50.0–35.0	100.0–71.0	0.0–0.5	Coarse Sand
0.707–0.500	35.0–25.0	71.0–50.0	0.5–1.0	
0.500–0.354	25.0–18.0	50.0–35.0	1.0–1.5	Medium Sand
0.354–0.250	18.0–13.0	35.0–25.0	1.5–2.0	
0.250–0.177	13.0– 9.0	25.0–18.0	2.0–2.5	Fine Sand
0.177–0.125	9.0– 6.0	18.0–13.0	2.5–3.0	
0.125–0.088	6.0– 4.0	13.0– 9.0	3.0–3.5	Very Fine Sand
0.088–0.062	4.0– 3.0	9.0– 6.0	3.5–4.0	
0.062–0.044	3.0– 2.0	6.0– 4.0	4.0–4.5	
0.044–0.031	2.0– 1.5	4.0– 3.0	4.5–5.0	Silt
0.031–0.022	1.5– 1.0	3.0– 2.0	5.0–5.5	
0.022–0.016	1.0– 0.7	2.0– 1.5	5.5–6.0	

* A simple conversion chart can be drawn up for converting phi units to millimeter diameters by plotting the above data on semilogarithmic paper using the arithmetic scale for phi units and the logarithmic scale for diameters in millimeters. The curve is the straight line given by $\text{Log}_{10}\, d = 0.301\phi$, where d is the diameter of the grains in millimeters and ϕ is the phi size interval. Cf. W. C. Krumbein and F. J. Pettijohn, *Manual of Sedimentary Petrography* (New York: D. Appleton-Century Co., 1938), p. 244.

At first in attempting to measure the size of projected grains, a series of concentric circles were drawn on a card with radii corresponding to the class intervals. The grain size was then determined by

and the statistical moments are calculated by using standard methods.

Comparison of weight (sieving) and numerical frequency data.—Most analytical size studies of sand are done by sieving the sand and weighing the amount retained upon each sieve. Statistical analysis and interpretation can be applied equally well to either numerical or weight data, yet results secured by one method cannot be directly compared with those secured by the other method. The use of numerical data shifts the cumulative curve together with all its parameters towards the fine direction,

[5] Square sieve openings are defined by the lengths of their square sides. Actually, the maximum opening of the sieve would be the diagonals of these squares, the length of which is 1.414 longer than the sides. This "oversize" would only be effective in the case of the micas and other similar minerals. For all practical purposes, at least in the sand grain range, the above comparison between the sieving and projected class intervals will hold good.

and the use of weight data shifts it towards the coarse direction (Hatch, 27–37). This is obvious, as a single coarse grain has a numerical frequency of one but a weight frequency equal to many small grains. If the frequency-distribution curve of a sediment plots essentially as a straight line on probability graph paper, it has a normal distribution. The two lines of the weight and numerical distributions will be parallel and will differ only by the shift along the size axis. If the frequency-distribution curve is skewed, there is the same kind of shift along the size axis but the slope or shape of the frequency curve may also change. Therefore, it follows that at least one of the parameters must change. However, the effect of skewness is not great unless the skewness is extreme.

Assuming that a sand is monomineralic or made up of minerals of essentially the same specific gravity (which assumption is usually not greatly in error for the sand-grade sizes) and that the grains have a normal size distribution, then the arithmetic means derived from count frequency and those derived from weight frequency can be transformed from one to the other if certain empirical corrections are applied.

Transformation from numerical to weight frequency data.—The theory of the transformation is based upon work done by Hatch and Choate (369–387). In a later paper by Hatch (30–32), the equation

$$Ln M_{gw} = Ln M_{gc} + 3.0 Ln^2 \sigma_{gwc}$$

is derived, where Ln is the natural logarithm, M_{gw} is the geometric weight mean, M_{gc} is the geometric counting mean and σ_{gwc} is the geometric standard deviation for either counting or weight determination since the geometrical standard deviation for count and for weight determinations are equal for a normal size distribution. But "the phi mean, when transformed to its diameter equivalent, becomes the geometric mean of the size distribution. In other words, the phi mean is the negative logarithm to the base 2 of the geometric mean of the grain diameters" (Krumbein and Pettijohn, 243–244). Likewise, the logarithm of the geometric standard deviation is equivalent to the phi standard deviation. Therefore, the equation may be written for conversion of count data to weight data as:

$$M_{\phi w} = M_{\phi c} - 2.08\sigma_{\phi c}^2 + C$$

and for conversion of weight data to count data as:

$$M_{\phi c} = M_{\phi w} + 2.08\sigma_{\phi w}^2 - C$$

where $M_{\phi w}$ is the phi mean of the weight distribution, $M_{\phi c}$ is the phi mean of the count distribution, $\sigma_{\phi c}$ is the phi standard deviation of the count distribution, $\sigma_{\phi w}$ is the phi standard deviation of the weight distribution and C is a constant which has been added to the equation to take care of the empirically determined sieving corrections.

Experimental data by Hatch and Choate (369–387) and later by Hatch (27–37) amply verify the equations derived by Hatch for the size range within Stokes' law. Considerable work has been done at the United States Soil Conservation Service Laboratory, Pasadena, California, on the transformation of weight frequency sieve analysis data to both weight and number diameter data. This work extended to particles as large as one-half millimeter which is well beyond the Stokes' range. The distributions studied were mainly normal or slightly skewed sieve analyses of pure quartz sands whose sphericity and roundness increased rapidly with increasing size. It was found that curves for the weight frequency and number frequency data were nearly parallel lines on logarithmic probability paper, irrespective of the average size. It was concluded that for all ordinary work the two techniques are interchangeable except that the transformation constant for the phi mean size has to be determined by *direct experiment* for *every sand used*, for *each set of sieves*, and for *each change in sieving technique*. The phi standard deviation and skew-

ness, however, appear to be little affected.[6]

Mathematical studies by Rouse indicate that relatively simple mathematical types of size frequency distributions may be expected in sedimentation studies of homogeneous units. The fact that (1) the maximum horizontal intercept and the b-axis, both of which give numerical frequency data, (2) the true nominal diameter which can be used to give either weight or numerical frequency data, and (3) sieving, which gives weight frequency data, will in general show the same mathematical type of frequency distribution—namely, a logarithmic Gram-Charlier series of one or two terms—is evidence that a fundamental statistical law underlies all size data.

Table 2 gives a comparison of certain data derived from both sieve and count analyses of several sands. An examination of this table shows that the standard deviations are essentially the same for either mode of determining the size distribution. It is of interest to note that for the set of sieves used, sieving technique, and size distribution, the two methods give essentially the same means. It was found that to make a direct comparison of the results by using the above equations for the particular beach and dune sands given in Table 2, the empirical sieve and sieving technique correction is 0.35 phi units.

For commercial work it is not practical to determine the experimental corrections for each series of sieves, for each sieving technique, and for each sand sample in order that the two methods can be compared by means of the Hatch equations. It must only be remembered that (1) numerical data *cannot* be converted directly into weight data, and that (2) so long as *one system is used throughout the entire investigation*, all the data can be compared and correlated. It should also be remembered that a comparison of sieving data derived by using different sets of sieves and sieving techniques, as is bound to happen if data from different laboratories are compared, must be done with extreme caution if the sieving corrections are not known.

[6] *G. H. Otto, oral communication.*

Shape Determinations

The shape of grains is most readily determined by taking the square root of the ratio of the short and long diameter of the projected image of the same 50 grains that are used in the size analysis. The shape mean and any other moments can then be calculated by the usual methods. This method of shape determination has been described elsewhere (Pye and Pye).

Roundness Determinations

Roundness determination of sand grains can be made most readily by visually comparing their projection outlines with a standard roundness chart such as the one prepared by Krumbein (64–74). This chart designates the most angular grains as 0.1 and the best rounded as 1.0. However, the grains should first be examined under the microscope, especially, if they came from indurated sediments to be sure that their outlines are the true outlines of the grains as they were deposited and not the outlines of any attached carbonate cement, silica cement or other material. Such enlarged outlines, if formed subsequent to the deposition of the grains, will give erroneous information as to the condition of the grains at the time of their deposition. If roundness projection analysis is impossible, determination must be based upon microscopic study so that the original outlines of the grains can be used. The subjective element of associating a high roundness with a high sphericity or low roundness with a low sphericity must be guarded against. However, for rapid quantitative work the estimation method can be used, but for all practical purposes the descriptive terms given in Table 3 are equal good or better.

TABLE 2.—*Comparison of numerical frequency and weight frequency data*

Size mm.	Phi Size	Sample A			Sample B			Sample C			Sample D			Sample E		
		Frequency %			Frequency %			Frequency %			Frequency %			Frequency %		
		Numerical		Weight	Numerical		Weight	Numerical		Weight	Numerical		Weight	Numerical		Weight
		50 Grains	50 Grains	37 Grams Sieving	50 Grains	50 Grains	62 Grams Sieving	200 Grains	304 Grains	28 Grams Sieving	100 Grains	300 Grains	25 Grams Sieving	50 Grains	3000 Grains	23 Grams Sieving
1.00 –0.71	0.0–0.5	—	—	—	—	—	—	—	—	0.2	—	—	—	—	—	—
0.71 –0.50	0.5–1.0	—	—	—	—	—	.13	1.0	.7	3.2	—	.3	1.0	—	—	.1
0.50 –0.35	1.0–1.5	2	2	2.22	4	8	3.61	7.0	5.9	3.78	11	5.0	12.2	2	1.4	2.0
0.35 –0.25	1.5–2.0	10	6	19.45	20	12	20.95	41.0	40.5	28.28	48	49.3	37.4	32	34.2	15.3
0.25 –0.177	2.0–2.5	42	44	27.72	64	70	51.20	37.0	37.5	55.37	29	25.3	41.2	40	39.2	56.6
0.177–0.125	2.5–3.0	40	38	33.03	12	10	23.50	12.0	12.5	11.85	11	9.3	7.9	22	22.7	25.2
0.125–0.088	3.0–3.5	6	10	17.09	—	—	.52	1.5	2.6	.36	1	.7	.3	4	2.3	.6
0.088–0.062	3.5–4.0	—	—	.39	—	—	—	.5	.3	.02	—	—	—	—	.3	.2
Phi Mean		2.44	2.49	2.49	2.17	2.16	2.23	2.07	2.04	2.13	1.96	1.90	1.90	2.22	2.21	2.29
Phi Standard Deviation		.41	.42	.53	.34	.36	.45	.46	.46	.37	.43	.42	.46	.44	.42	.37

Sample A.—St. Peter sandstone, Twin City Brick Yards, St. Paul, Minn. (H-117)
B.—Dune sand, "Blow-out," ¼ mile back from Lake Michigan, Pentwater Heights, Mich.
C.—Dune sand from Lake Michigan, Furnessville, Ind. (D-1A)
D.—Dune sand from Lake Michigan, Furnessville, Ind. (D-2A)
E.—Dune sand from Lake Michigan, Furnessville, Ind. (D-3A)

TABLE 3.*—*Relationship between roundness scales*

Descriptive Term	Wadell's Roundness	Russell's Roundness
Angular	0.00–0.16	0.00–0.15
Sub-angular	0.16–0.25	0.15–0.30
Sub-rounded	0.25–0.40	0.30–0.50
Rounded	0.40–0.63	0.50–0.70
Well rounded	0.63–1.00	0.70–1.00

* *Table compiled by F. J. Pettijohn.*

Recording of Data

Figure 2 illustrates a simple form for recording projection data. The a- and b-axes are first measured and then the sphericity is calculated and tabulated in the appropriate spaces. The b-axes are likewise tabulated and recorded to give the size data. As many of the parameters as are desired are then calculated, using the equations indicated. Certain short-cuts will become apparent as the data sheet is used. Thus, for example, if the class interval is one-half and fifty grains are used, the mean will be given by moving the decimal point two places to the left and by subtracting or adding (depending upon the sign) the total of the *fd* column from the mid-point of the *d* scale.

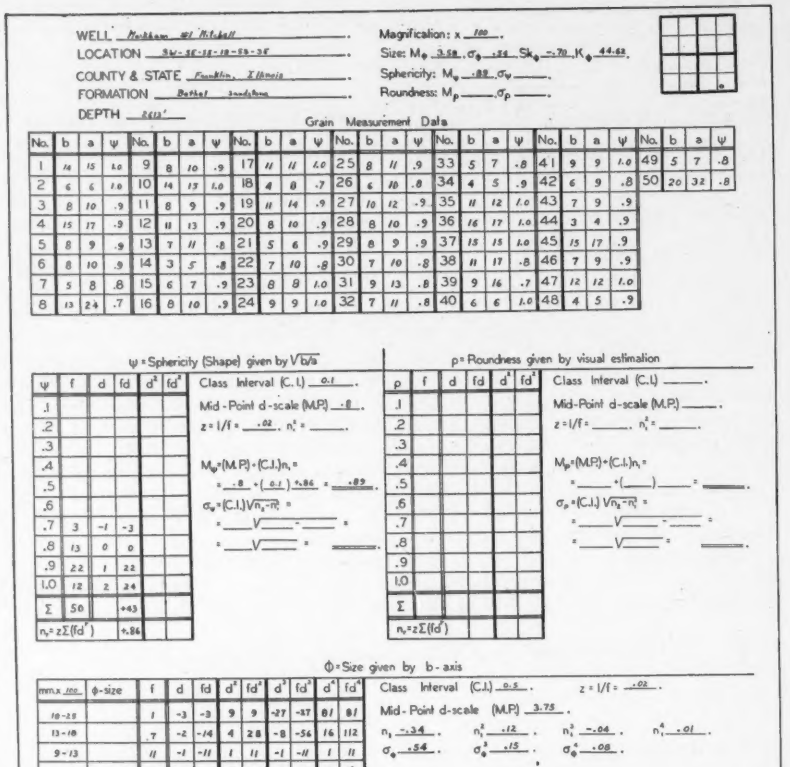
Thin-Section Analysis

Size Analysis and Comparison with Projection Size Analysis

Since the method of size analysis by thin-section has been adequately described elsewhere (Hagerman, Krumbein and Pettijohn, 129–133, 176–180), it need not be discussed here. A comparison of results obtained by thin-section analysis and those obtained by projection analysis of grains from the opposite half of the core from which the thin-section was made, are shown in Table 4. It should be noted that the thin-section analysis was made with the projector using the same magnification as was used in the projection method. However, the size distribution was obtained by using the maximum *horizontal* diameter and then corrected as recommended by Krumbein and Pettijohn (129–133, 176–180). In order to aid in distinguishing grain boundaries of the thin-section it was

TABLE 4.—*Comparison of projection analysis and thin-section analysis*

Well and Location	Depth	Projection Analysis			Thin-Section Analysis		
		No. Grains Measured	M_ϕ	σ_ϕ	No. Grains Measured	M_ϕ	σ_ϕ
Kingwood, First Nat. Bank of Woodlawn 4, Sec. 13, T. 1 S., R. 2 W.	1941–1942	50	3.46	0.36	50	3.53	0.59
Adams Oil and Gas, Merryman 17, Sec. 21, T. 4 N., R. 1 E.	1406	50	3.54	0.42	50	3.51	0.53
Gass, Keston 1, Sec. 13, T. 1 S., R. 2 W.	1541	50	2.73	0.59	50	2.75	0.65
Gass, Keston 1, Sec. 13, T. 1 S., R. 2 W.	1541				50	2.58	0.74
Gass, Keston 1, Sec. 13, T. 1 S., R. 2 W.	1541				186	2.85	0.74
Gass, Keston 1, Sec. 13, T. 1 S., R. 2 W.	1541				190	2.62	0.56
Gass, Keston 1, Sec. 13, T. 1 S., R. 2 W.	1541				376	2.73	0.65



WELL Markham #1 Mitchell
LOCATION SW-SE-SE-19-8S-3E
COUNTY & STATE Franklin, Illinois
FORMATION Basal Sandstone
DEPTH 2613'

Magnification: x 100
Size: M_ϕ 3.58, σ_ϕ .54, Sk_ϕ -.70, K_ϕ 44.62
Sphericity: M_ψ .88, σ_ψ ——
Roundness: M_ρ ——, σ_ρ ——

Grain Measurement Data

No.	b	a	ψ	No.	b	a	ψ	No.	b	a	ψ	No.	b	a	ψ	No.	b	a	ψ	No.	b	a	ψ	No.	b	a	ψ
1	14	15	1.0	9	8	10	.9	17	11	11	1.0	25	8	11	.9	33	5	7	.8	41	9	9	1.0	49	5	7	.8
2	6	6	1.0	10	14	13	1.0	18	4	8	.7	26	6	10	.8	34	4	5	.9	42	6	9	.8	50	20	32	.8
3	8	10	.9	11	8	9	.9	19	11	14	.9	27	10	12	.9	35	11	12	1.0	43	7	9	.9				
4	15	17	.9	12	11	13	.9	20	8	10	.9	28	8	10	.9	36	16	17	1.0	44	3	4	.9				
5	8	9	.9	13	7	11	.8	21	5	6	.9	29	8	9	.9	37	15	15	1.0	45	15	17	.9				
6	8	10	.9	14	3	5	.8	22	7	10	.8	30	7	10	.8	38	11	17	.8	46	7	9	.9				
7	5	8	.8	15	6	7	.9	23	8	8	1.0	31	9	13	.8	39	9	16	.7	47	12	12	1.0				
8	13	24	.7	16	8	10	.9	24	9	9	1.0	32	7	11	.8	40	6	6	1.0	48	4	5	.9				

ψ = Sphericity (Shape) given by $\sqrt{b/a}$

ψ	f	d	fd	d^2	fd^2
.1					
.2					
.3					
.4					
.5					
.6					
.7	3	-1	-3		
.8	13	0	0		
.9	22	1	22		
1.0	12	2	24		
Σ	50		+43		
$n_s = z\Sigma(fd^2)$			+.86		

Class Interval (C.I.) 0.1.
Mid-Point d-scale (M.P.) -.8.
$z = 1/f$ = .02. n_s^2 = ——.

M_ψ = (M.P.) + (C.I.)n_s =
= -.8 + (0.1) +.86 = .89.

σ_ψ = (C.I.)$\sqrt{n_s - n_s^2}$ =
= ——$\sqrt{\quad - \quad}$ =
= ——$\sqrt{\quad}$ = ——.

ρ = Roundness given by visual estimation

ρ	f	d	fd	d^2	fd^2
.1					
.2					
.3					
.4					
.5					
.6					
.7					
.8					
.9					
1.0					
Σ					
$n_r = z\Sigma(fd^2)$					

Class Interval (C.I.) ——.
Mid-Point d-scale (M.P.) ——.
$z = 1/f$ = ——. n_r^2 = ——.

M_ρ = (M.P.) + (C.I.)n_r =
= —— + (——) —— = ——.

σ_ρ = (C.I.)$\sqrt{n_r - n_r^2}$ =
= ——$\sqrt{\quad - \quad}$ =
= ——$\sqrt{\quad}$ = ——.

Φ = Size given by b-axis

mm x 100	φ-size	f	d	fd	d^2	fd^2	d^3	fd^3	d^4	fd^4
18-25		1	-3	-3	9	9	-27	-27	81	81
13-18		7	-2	-14	4	28	-8	-56	16	112
9-13		11	-1	-11	1	11	-1	-11	1	11
6-9	4.0-3.5	22	0	0	0	0	0	0	0	0
4-6		7	1	7	1	7	1	7	1	7
3-4		2	2	4	4	8	8	16	16	32
Σ		50		-17		63		-71		243
$n_\phi = z\Sigma(fd^2)$				-.34		1.26		-1.42		4.86

Class Interval (C.I.) 0.5. $z = 1/f$ = .02.
Mid-Point d-scale (M.P.) 3.75.
n_1 -.34. n_1^2 .12. n_1^3 -.04. n_1^4 .01.
σ_ϕ .54. σ_ϕ^2 .15. σ_ϕ^3 .08. σ_ϕ^4 .08.

M_ϕ = (M.P.) + (C.I.)n_1 = 3.75 + (0.5) -.34 = 3.58.
σ_ϕ = (C.I.)$\sqrt{n_2 - n_1^2}$ = (0.5)$\sqrt{1.26 - .12}$ = (0.5)$\sqrt{1.14}$ = .54.
$m_3 = n_3 - 3n_1n_2 + 2n_1^3$ = -1.42 -3(1.26)(-.34) +2(-.04) =
= -1.42 - (-1.29) + (-.08) = -.21.
$Sk_\phi = m_3/2\sigma_\phi^3$ = -.21 /2(.15) = -.21 / .30 = -.70.
$m_4 = n_4 - 4n_1n_3 + 6n_1^2n_2 - 3n_1^4$ = 4.86 -4(-.34)(-1.42) +6(.12)(1.26) -3(.01) =
= 4.86 - 1.93 + .91 - .03 = 3.81.
$K_\phi = (m_4/\sigma_\phi^4) - 3 = [(3.81)/(.08)] - 3 = 47.62 - 3 =$ 44.62.

Geometric Measures: M_ϕ 2.894 ; σ_ϕ .463. (mm.)
Notes:

(mineralogy, petrography, etc., over)

FIG. 2.—Form for recording and calculating data.

necessary to equip the projector with polaroids. A partial crossing of them gave a better definition of the grains than when they were completely crossed. Exact outlines of the grains were rather difficult to determine and secondary filling of pores by quartz and clay material made the thin-section analysis much more difficult and somewhat less accurate than the individual grain analysis.

An examination of Table 4 shows that in most cases the mean size of the grains given by thin-section analysis is close to that given by projection analysis but usually the sorting is poorer. The data from the Bethel sandstone core from Gass, Keston 1, clearly shows one characteristic of thin-section analysis—it permits the analysis of individual, very narrow sedimentation units. A preliminary study of the thin-section revealed minute bedding which caused bands of varying grain-size distribution. The first four thin-section analyses of this core are from different fields on the same slide and each one represents one of the microscopic beds; the last analysis, using 376 grains, is a composite of several fields and includes several of the bands. In general, one field will not be representative of the slide as a whole, as is shown by the variation in the first four fields. The last test using several fields is much more representative of the slide as a whole and closely approaches the results given by the projection data, since the grains used for projection usually were selected to represent the entire thickness of the core biscuit and took in grains from all bands.

Roundness Determination

Roundness determinations for thin-section work are estimated by comparing the grain outlines with those of a standard roundness chart (Krumbein, 64–74). A numerical roundness value or a descriptive term is then assigned. Frequently the quartz grains in the thin-sections and those mounted in oils show a portion of the original grain outline as it was prior to secondary enlargement. From these portions of original outlines an estimation of the roundness of the grains may be made. It is of interest to note that the roundness of some grains from well-indurated Bethel sandstone cores was estimated from the thin-section as being in the neighborhood of 0.6 for all grains, while the projected roundness appeared to lie between 0.3 and 0.4. The difference was due to the secondary silica enlargement which remained attached to the projected grains so that they presented extremely angular outlines.

Polished Section Analysis

A number of very interesting relationships, especially those relating to pore patterns, may be worked out from the study of polished sections. These can be made very rapidly and yield much valuable data to supplement other methods of study. In fact, they can be made to yield almost as much data as thin-sections and many of the nonopaque minerals can be identified after considerable practice, although no polarization effects are obtainable. The sections are viewed either with vertical illumination using a metallographic microscope or with incident illumination. In either case, the pore relations stand out very markedly.

All of the Bethel sandstone samples were impregnated with colored bakelite diluted with bakelite thinner. The sample was submerged in the bakelite so that at least three sides were covered and then placed under a bell jar. Partial evacuation by a water pump reduced the pressure and caused some of the air in the core to escape. When no more bubbles appeared at the surface of the bakelite, air was admitted into the bell jar. The increase in pressure drove the bakelite into and through the pores of the core. Impregnation as deep as a quarter of an inch was secured by this method, which depth is ample for any polished-section work. The sample was then removed from the bakelite, cured and polished on all three sides. The polished samples yielded data

in two directions perpendicular to each other and to the bedding-planes and in one direction parallel to the bedding-plane.

In a second method which greatly shortens the time of preparation, Canada balsam is used as the impregnating medium. It is diluted and then mixed with an organic dye soluble in xylol. A brilliant green or blue is very satisfactory; red may obscure hematite cement or oxidation products of iron-bearing minerals. The dyed balsam is cooked and poured into dishes, such as petri dishes, and then is ready for use. Flat surfaces are first ground on the core chips after which they are placed in a dish containing the balsam. The balsam is then heated to about 300°F. At this temperature, the balsam will not decompose but will be fluid enough to deeply penetrate the core since at high temperatures balsam has a very high wetting effect towards quartz and most other minerals. The core is either first heated to the same temperature as the balsam or is left in the balsam long enough to reach a temperature equilibrium.

Polishing may be rapidly done on rotating laps in the same manner as for ore specimens although very coarse grinding powder tends to pit the section badly. Final grinding is with 902 carborundum powder followed by the use of a felt lap wet with a suspension of green chromic oxide in water.

If care is taken not to melt the balsam by over-heating the specimen, it can quickly be ground down by using increasingly fine sheets of carborundum abrasive paper attached to a rotating wheel such as Short (43–44) describes for use in polishing ore specimens. Chromic oxide is used for the final polishing.

Study of Grains Mounted in Index Liquids

After the grains have been examined by means of the projector, it is often advantageous to mount a representative number on a slide and to study them in detail under the polarizing microscope. Mounting is usually in clove oil, although for special cases media of other indices of refraction may be employed. Secondary enlargements, roundness, shape, mineral composition, inclusions and alterations are revealed as clearly as in a thin-section, and preparation is much more rapid. The main drawback to this method is the fact that grain relationships cannot be studied.

By tilting the microscope stage slightly and rotating it, the grains can be made to roll about in the mounting medium allowing a better study of the grains and inclusions as well as yielding a three-dimensional picture of their shape and roundness. A comparison of the results with those derived by the projection method further confirms the fact that except for micaceous grains the two dimensional shape measurement given by the projector is satisfactory in nearly all cases.

Frequently, it is interesting to examine the grains under incident illumination and since medium to high power magnification is often necessary it may be difficult to secure adequate illumination. To remedy this a small pen-flashlight is useful. It may be convenient to remove the head of the flashlight and tape the bulb to the battery but leave the bulb projecting well beyond the battery and case. A number "1" bulb is small enough to insert between the objective and slide except when a very high powered objective is used. Touching the bulb with blue ink gives a "day-light" quality to the illumination although this cuts down on the intensity of light.

Heavy Mineral Separations

In a few cases it may be desirable to make heavy mineral concentrates. Any of the heavy liquids are suitable as a separation medium. Filtration is speeded up by filtering into a flask partially evacuated by means of a water pump and by substituting for the ordinary filter paper a square of finely woven and not

too heavy white cloth. Filtration, washing and removal of the residue is much more satisfactory, rapid and cheaper when cloth is used instead of filter paper.

Laboratory Errors

In a sedimentational study using the above shortened techniques, there are four main sources of laboratory error: (1) selection of grain samples, (2) clay residues, (3) secondary enlargement of grains, (4) errors due to using too small a sample.

Selection of Grain Samples

A primary source of error consists in the fact that a sandstone is composed of a number of layers or beds, each differing in some slight degree from the immediately adjacent ones. The layers are normally but a few millimeters thick and only slightly different from each other. Sampling of grains from a core or hand specimen may consist of either selecting grains from a single thin bed or lens, or taking a composite sample uniformly over an entire surface freshly broken perpendicular to the bedding. The determination of which method of sampling shall be used is entirely dependent upon the purpose of the study. If the hydraulic conditions under which each layer was laid down is desired, then care must be taken to sample each layer individually. If the "mass properties" of the sand are of primary importance, a uniform sample over the entire face of the specimen perpendicular to the bedding must be taken.

Tests were run to determine whether the securing of grains by brushing might introduce selective errors. Areas where grains are weakly cemented, where there is an excessive amount of fine material, or where grains are so well cemented that cross-fracturing occurs, will introduce bias. Examination under the microscope shows that rarely among the quartz grains does cross-breaking result from brushing, although tourmaline and some other grains with well developed cross-fractures or cleavage may break. Only rarely are aggregates found and these can always be readily distinguished and resolved into their components by varying the focus of the projector. In cases where harder cemented nodules of sand are found there is selection in the grains brushed off, but thin-sections revealed that, in the case of the Bethel sandstone at least, these zones of harder cementation nearly always consist of carbonate and carry a grain distribution not different from the rest of the sand. Weak shale zones are also selectively removed, but this normally appears as clay in the mount and offers no difficulty, except for making it "dirty."

Clay Residues

Systematically in the projection analysis of sandstone samples any residues finer than 0.01 mm. were ignored. This procedure is followed since these residues are in very minor proportions in the sand lenses. Their abundance in some slides is due to (1) the thin shale bands and lenses marking bedding-planes (a mixing of sedimentation units), or (2) the result of disaggregation of the grains themselves. Fine material arising during disaggregation comes (1) from shale granules and fragments which hydraulically act similar to coarser sand grains but upon analysis are broken down to their individual grain components, (2) from clay that adhered to the sand grains either during earlier periods of deposition or transportation, (3) from fragments broken off the original sand grains either as fracture fragments or cleavage flakes, (4) from mafic minerals which were badly altered and decomposed either prior to deposition or after deposition and which on analysis break down from coarse grains to a multitude of fine clay or chlorite flakes, and (5) from fragments from secondary cement and enlargement of the grains. Of these latter, carbonate frequently shows up as freshly fractured rhombs, and silica appears either (a) as curved shells that fitted around the

original grains, (b) as sharp triangular fragments formed where the enlargement fitted between other sand grains, or (c) as fragments showing portions of crystal faces of quartz, especially the pyramids.

None of the above types of fines is primary to the sediment and therefore should not be counted as grains. This is especially true for the shale granules which should be studied as an aggregate rather than as the individual components. Certainly some fine clay was deposited as such but it would be impossible to determine what percentage of the clay found in the projected slide is the result of the preparation of the sample for analysis and what percentage should naturally be present. Further difficulties are that measurement errors become of increasing importance as the definition of boundaries becomes poorer in the finer grains and the individual grains are harder to resolve and separate.

Secondary Enlargement

Secondary enlargement and cement possibly introduce the most serious error. Almost all quartz grains show some secondary enlargement in siliceously cemented sandstones. Usually this is but a small percentage of the original diameter of the grain, being but little more than a thin envelope. Examples have been observed, however, where the cross-sectional diameters of the grains, as revealed by thin-sections, may be increased fifty per cent or more. Except for these unusual cases, even though there has been enlargement, it is probably not sufficient to change radically the size distribution picture. The same is true for shape analysis since in many sandstones the enlargement is almost uniform on all sides of the original grains. The effect of enlargement can usually be ignored since for most work it is a waste of time to determine shape values beyond the nearest tenth.

Roundness is the grain parameter which is most seriously affected by secondary enlargement and it can be determined only by thin-section or grain study under the microscope. However, it is well to examine enough samples under the microscope to determine the effect enlargement may have upon all parameters.

Errors Due to Use of Small Samples

Preliminary investigations over a number of years by the writer indicated that the use of 300 grains, which number has usually been considered standard for determining the physical properties of a sand sample, is excessive except possibly for mineral counts. A series of studies has been carried out to determine how few grains need be counted to yield satisfactory results.

Laboratory investigations.—To ascertain the optimum number of grains to be studied, more than 40 fields were selected from representative sand samples that varied in origin from beach sands to sandstone out-crops and oil well cores. Various fields from the same slide and from duplicate slides made up from the same samples were also run to test the uniformity of the slide and the reproducibility of results as well as the reproducibility of making slides by brushing off grains.

The method employed in running the tests consisted of selecting a random field on a slide and measuring 25, 50, 75, 100, 200, and 300 grains for each field selected. To avoid making a biased selection of grains, roughly concentric circles were drawn so that each circle included what was estimated to be 25, 50, etc. number of grains and only grains in these circles were measured. The results of some of these tests are shown in Tables 5, 6, 7, and 8.

Usually it was found that the runs were entirely reproducible. In the size analysis, it was found that using only 50 grains gave a relative error usually less than 2 per cent and the per cent of difference was under 10 per cent. Assuming that the use of 300 grains gives the true mean, then the approach to this mean

TABLE 5.*—*Comparison of size data derived from counting 50, 100, 150, 200, and 300 grain samples and the reproducibility of the results*

Sample D-3A: Dune sand from near Lake Michigan, Furnessville, Indiana

Slide No.	Test No.	50 Grains			100 Grains		150 Grains		200 Grains		300 Grains	
		M_ϕ		σ_ϕ	M_ϕ		M_ϕ		M_ϕ		M_ϕ	σ_ϕ
		H	*I*	*I*	*H*	*I*	*H*	*I*	*H*	*I*	*I*	*I*
1	1	1.90	2.11	0.41	1.89	2.13	1.96	2.15	1.99	2.18	2.18	0.42
	2	1.88	2.14	0.42	2.09	2.23	2.02	2.20	2.01	2.18	2.23	0.44
	3	2.10	2.21	0.45	2.02	2.18	2.05	2.20	2.05	2.20	2.21	0.41
	4	2.09	2.25	0.39	1.97	2.17	2.04	2.20	2.00	2.18	2.20	0.43
	5	1.97	2.13	0.42	1.99	2.18	1.97	2.15	1.95	2.15	2.23	0.43
	6	2.05	2.22	0.44	2.03	2.19	1.94	2.16	1.98	2.17	2.19	0.42
2	7		2.24	0.41							2.22	0.44
	8		2.26	0.52							2.20	0.43
	9		2.28	0.40							2.20	0.42
	10		2.20	0.43							2.22	0.43

Summary Sample D-3A

	Intercept Mean Size (mm.)	
	50 Grains	300 Grains
Average of the Means	2.20	2.21
Standard Deviation of the Means	0.031	0.003
Relative Error (Per cent)	1.71	0.48

* *H* = Maximum horizontal intercept *I* = *b*-axis measurement
M_ϕ = Mean phi size σ_ϕ = Phi standard deviation

The maximum horizontal intercept is recommended by W. C. Krumbein, "Thin-section Mechanical Analysis of Indurated Sediments," *Jour. Geol.*, Vol. XLIII (1935), pp. 482–496, for thin section size analysis. However, without a correction factor it cannot be used for projection analysis.

So that this dune sand could be treated as an indurated sandstone, it was thoroughly mixed and cemented with lime. After thorough setting it was split open and each slide was made by brushing off a representative sample of grains from one of the inner surfaces of the "rock." This table shows the reproducibility of successive fields taken from the same slide (the fields were taken in definite order over the slide), and gives a comparison between two different slides made up from the same face of the same "rock."

by increasing the number of grains measured is very gradual after 50 grains for a size analysis and equally as gradual after 25 grains for roundness and sphericity determinations. The gradual approach is due to the fact that the error of the mean of a set of observations varies inversely as the square root of the number of observations. (Krumbein and Pettijohn, 41–43.)

In some of the work, the fields were selected according to a definite pattern over the slide to test the uniformity of distribution of grains. Again, results were entirely reproducible among the different fields except in a few rare cases usually found near the edges of the slide. It was obvious from visual examination prior to any measurements that the results from those edge-fields would not correspond to results from elsewhere on the slide. During routine analysis, such areas would never be selected as representative of the slide as a whole.

The general conclusion of the study was that if the distribution of grains is

TABLE 6.*—*Comparison of size data derived from counting 50, 100, 200, and 300 grain samples and the reproducibility of the results*

Sample D-2A: Dune sand from near Lake Michigan, Furnessville, Indiana

Slide No.	Field No.	Mean Size in Phi Units							
		50 Grains		100 Grains		200 Grains		300 Grains	
		H	*I*	*H*	*I*	*H*	*I*	*H*	*I*
1	1	1.75	1.99	1.76	1.97	1.74	1.94	1.73	1.94
1	2	1.77	1.94	1.72	1.92	1.73	1.91	1.66	1.86
2	1	1.73	1.97	1.60	1.82	1.66	1.87	1.75	1.97
2	2	1.71	1.87	1.74	1.98	1.67	1.88	1.74	1.93
3	1	1.70	1.87	1.72	1.92	1.68	1.89	1.71	1.90
3	2	1.51	1.77	1.72	1.93	1.69	1.92	1.65	1.88

* *H* = Maximum horizontal intercept *I* = *b*-axis measurement

This table shows the reproducibility of fields from the same slide and of slides made up from the same "rock." The dune sand was made into an artificial "rock" with line cement.

TABLE 7.*—*Uniformity of fields over a slide*

Core from Gass, Keston 1, Sec. 13, T. 1 S., R. 2 W., Washington County, Illinois; Depth 1543 feet

50 Grains			300 Grains		
Test No.	M_ϕ	σ_ϕ	Test No.	M_ϕ	σ_ϕ
1	2.70	0.70	1	2.73	0.65
2	2.79	0.66	2	2.76	0.60
3	2.84	0.69	3	2.74	0.65
4	2.69	0.70	4	2.75	0.60
5	2.62	0.52	5	2.71	0.60
6	2.74	0.59	6	2.78	0.65
7	2.52	0.47	7	2.79	0.63
8	2.88	0.63	8	2.70	0.61
9	2.81	0.66	9	2.73	0.60
10	2.80	0.56	10	2.76	0.66
11	2.85	0.57			
12	2.70	0.60			
Average	2.74	0.61		2.75	0.62

* M_ϕ = Mean phi size
σ_ϕ = Phi standard deviation

The test numbers of the 50 and 300 grain samples do not represent the same field, since to secure 300 grains usually involved measuring more than one field. All of these tests were run on a single slide covering the slide in a definite sequence. Fields 7 and 8 of the 50 grain tests did not appear "normal" to the eye and would not have been selected to represent the slide.

TABLE 8.*—*Reproducibility of slide made up from the same core*

Core from Carpenter-Goldberg, C.B.&Q.R.R. 1, Sec. 1, T. 1 N., R. 1 W., Clinton County, Illinois; Depth 1372–73 feet.

Test No.	50 grains	
	M_ϕ	σ_ϕ
1	3.15	0.46
2	3.14	0.46
3	3.11	0.43

* M_ϕ = Mean phi size
σ_ϕ = Phi standard deviation

A comparison of results based upon three slides made from three separate, freshly broken pieces of the same core biscuit.

statistically normal,[7] if the grains are uniformly scattered at random over the slide and if the spread of the distribution of the physical properties of the sand is not too great, then a study of 25 grains is

[7] To readily check whether the size distribution is normal, the analysis is plotted on logarithmic probability paper (to check shape and roundness distribution, arithmetic probability paper must be used). If the points fall on a straight line except for the coarse and fine tails, then the distribution is normal. If the points do not essentially fall on a straight line, the distribution is either not normal or too small a sample has been used.

adequate to determine the roundness and sphericity of the sample providing that the selection of grains studied is unbiased and random. For size determination, 50 grains is most representative of the distribution. To assure a random selection of grains, it is recommended for all work that a field on the slide which has a uniform and apparently normal distribution of grains be chosen and a circle drawn that will enclose about fifty grains. Those grains lying half way or more outside the circle should not be studied.

Theoretical investigations.—Recently Plumley has carried out a theoretical study of the above problem for shape and roundness and has reached the conclusion that only very small samples are required for these determinations when their distribution is statistically normal.[8]

[8] The normal distribution function can be written as

$$y=\frac{N\log_{10}eX^n}{\sqrt{2\pi}\log_{10}\sigma_g}e^{-k[(\log_{10}X-\log_{10}\bar{X}_g)/\log_{10}\sigma_g]^2}$$

where X^n is the general term which makes it possible to apply the equation to any distribution of properties that can be defined by that term. If the equation is transformed to phi-units, it is greatly simplified and becomes

$$y=Ae^{-[k[(\phi-M_\phi)/\sigma_\phi]^2+(0.694\phi)^n]}$$

where

$$A=-\frac{0.434N}{0.301\sqrt{2\pi}\sigma_\phi}$$

and k, N, M_ϕ, and σ_ϕ are constants for the given distribution. This can be written as

$$\log_e\left(\frac{y}{A}\right)=-\frac{k}{\sigma_\phi^2}(\phi-M_\phi)^2-0.694\phi^n.$$

R. P. Loveland and A. P. H. Trivelli, "Mathematical Methods of Frequency Analysis of Size of Particles," *Jour. Franklin Inst.*, Vol. CCIV (1927), p. 204, make the general statement that it is a peculiar property of this generalized equation that whether diameters, areas, volumes, or weights are measured, the same distribution law holds and the only difference is in the constants. Hatch and Choate, *op. cit.*, pp. 369–386, have shown that the specific surface and average volume of grains are functions of the above normal distribution equation. If the same process of integrating the above generalized function is followed, it can be proved that this function can also be used to express the roundness, shape, and all other properties of sand grains which have normal distributions, and even those showing a moderate degree of skewness.

A brief review of his analysis adapted to size distributions follows. The theory is based upon the equation of the standard error of the mean:

$$\sigma_m=\frac{\sigma}{\sqrt{n}}$$

where σ_m is the standard error of the mean, σ is the standard error of one grain and n is the number of grains sampled. However, a better result comes from using the "maximum error," which is equal to three times the standard error, or the error of the mean no larger than the required per cent in 99.7 cases out of a hundred. The equation thus becomes:

$$\sigma_{mm}=\frac{3\sigma}{\sqrt{n}}$$

where σ_{mm} is the maximum error of the mean.

Thus, if the standard deviation is known for a certain number of grains, the maximum error of the mean can be determined; or, if the standard deviation and maximum percentage of error of the mean tolerated is decided upon, then the number of grains to be examined can readily be determined to give this maximum tolerated error. It should perhaps be noted, that although the standard deviation has an effect upon the curves, it need only be approximately known. The less the deviation, the fewer the number of grains that must be investigated.

As an example of the use of the above, some 50 or 100 grains may be studied from several samples and the greatest spread of their means determined, such for example as 2.80 and 3.90, with an average of the means of 3.35. The average standard deviation is also found to be 0.4. To be sure that any significant change in the distribution will be noted, it is decided that at the maximum an error of 10 per cent of the mean from the true mean will be tolerated. Since the values will then fluctuate between 2.52 and 3.08, and 3.51 and 4.29 for the means, respectively, a 10 per cent

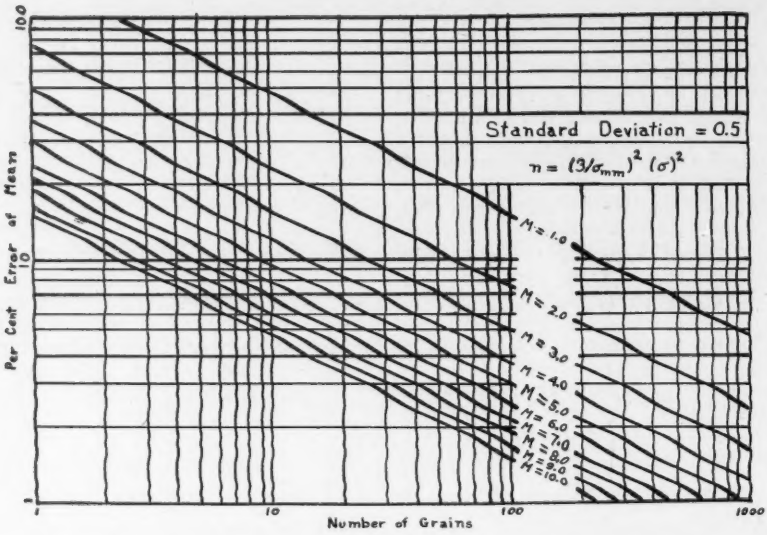


FIG. 3.—Chart for determining the number of grains to be studied if the maximum variation over the whole area under investigation is known.

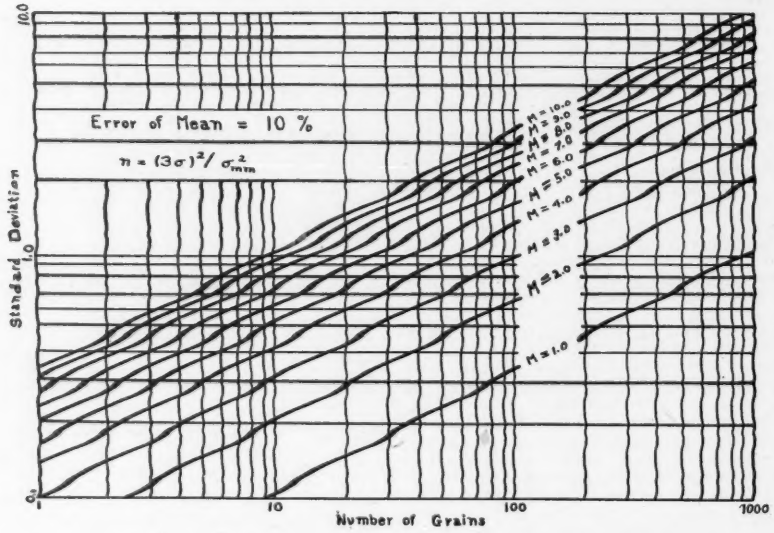


FIG. 4.—Chart for determining the number of grains to be studied if only one sample is being analysed.

error of the mean will not obscure any trends which may be present. Using Figure 3, and to be on the conservative side, a value of the mean one unit smaller (2.35) than the average and a standard deviation one tenth larger (0.5), it will be seen that only about 40 grains must be studied to keep the maximum error of the mean within the tolerated 10 per cent.

After this determination, it is simplest to study for all samples the above number of grains. However, if this is not desired, the number of grains to be studied for each point may be determined by using Figure 4. Ten grains arbitrarily selected and measured yield a mean of 3.50 and a standard deviation of 0.4; for precaution it is best to employ a mean one unit smaller (2.50) and a standard deviation one tenth higher (0.5). From Figure 4, this indicates 37 grains will be necessary to keep the percentage of error of the mean from the true mean within the tolerated 10 per cent.

The curves show that a decrease in degree of sorting calls for an increase in the number of grains measured in order to assure the same per cent of error and that a decrease in the per cent of error calls for an increase in the number of grains analyzed.

Thus the theoretical study, after the method of Plumley, yields the same general results as did the experimental work. However, for statistical manipulations 50 grains are more convenient than an odd number.

To summarize, it is felt that except in unusual cases the increased accuracy does not warrant the expenditure of the time and labor necessary to measure 300 grains. However, this is prefaced on the assumption (1) that the grain distribution is essentially normal, (2) that a reprsentative field is selected for measurement, and (3) that no bias is introduced in the selection of grains for measurement. However, the greater the departure from a normal distribution and the greater the accuracy desired, the larger is the number of grains that must be studied. Further, if it is desired to determine whether there is a trend in the distribution of some physical property of the grains over an area, the error of the mean between the observations must be less than the difference between those physical properties of the most extreme examples studied.

The question of whether or not the grains brushed from a core are representative of the sample will largely depend upon the sampling technique. A thin-section analysis can give the size distribution over much narrower horizons and can eliminate all mixing of sedimentation units. However, if an average thin-section analysis is made of the same core that has had a projection analysis made of it, the two will be found to yield almost identical results, showing that brushing—at least for certain types of indurated sandstones—does not introduce a bias such as selectively removing coarse and rounded grains while leaving the fine angular ones on the core surface. The artificially cemented cores which were analyzed bear out the same general conclusions. It is true, that soft shale bands in the sandstone may be selectively removed, but as pointed out in an earlier section, the fine shale fragments are not counted in an analysis. Also, knots of hard cement may hold some grains firmer than those in adjacent areas but frequently these knots have the identical size distribution found in the adjacent areas. If the sand is uniform in appearance and uniform in cementation, then no selective removal of grains occurs. Further testing over a wider range of sandstone types will prove whether or not the brushing technique can be applied to all types of indurated sandstones.

CONCLUSIONS

Future oil exploration will become increasingly dependent upon intensive detailed geological and geophysical methods. Once the tools have been devised, their adoption by commercial concerns

will depend upon their practicality. This paper has attempted to establish a "practical system of sedimentology" and yet one that sacrifices nothing to reliability in results. It has also established a simple means of securing fundamental data on the sedimentary parameters and pore relationships of well indurated sandstones.

Furthermore, in sedimentational studies, all data, except that for size distribution, is based upon numerical frequencies of the properties. To make sedimentational procedures "homogeneous," size too should be based upon numerical data. By the methods outlined in this paper, size determinations can be readily run on a numerical basis with (1) a great saving of time over sieving procedures, (2) a great ease of extending the analysis several grade sizes farther down into the silt range, (3) a great flexibility in selecting class intervals to best reveal the actual size distribution in the sediment, and (4) the complete elimination of the mineralogy or weight factor from the size distribution.

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USE OF PALEONTOLOGY BY THE OIL INDUSTRY*

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ABSTRACT

This paper discusses briefly various uses which have been made of paleontology by the oil industry in the past. Present uses of paleontology in correlation and sedimentation studies are discussed. Suggestions are made as to how paleontology can be of added value as an aid in the finding of petroleum.

"Paleontology is a study of the history of life."[1]

While the above definition may be satisfactory for academic purposes, to the stratigrapher and petroleum geologist, paleontology is a tool, or more precisely, a complex kit of tools. In the hands of the expert, when used with a knowledge of sediments, structure, and electrical logs, these tools permit the opening of successive drawers in nature's treasure chest in much the same manner as a skilled locksmith with his gadgets can work his way through a series of doors, which to the average person appear securely fastened. Yet, no locksmith ever conceived of so great a variety of tools as paleontology provides. The average petroleum geologist learns to recognize only a few of them, and, I regret to say, many paleontologists tend to depend almost solely upon "master keys" which they term "guide-fossils," or "zones," or "tops." These master keys worked well over limited areas when the key hole was a well not over 5,000 feet deep. Experience of the last few years in the Gulf Coast, however, has shown that more than a limited set of master keys is needed when the key-holes are wells over 10,000 feet deep, for the combinations of sedimentation and environment have changed.

It is not the purpose of this necessarily brief paper to supply a history of applied paleontology (Schenck) or even of micropaleontology (Croneis), for such histories are readily accessible. It will not be amiss, however, to point out that during the first two decades of this century, under the guiding aegis of the "anticlinal theory," the field mapping of structures was the principal method of locating production. At that time the field geologist determined the age and sequence of his formations by the aid of larger fossils which he found on the surface and mapped his structures with the aid of a plane table. It was during this period or prior thereto, that most of our surface formations were named and type sections for larger units were established.

With the advent of micropaleontology some 25 years ago and with the rapid increase in the use of rotary well cores, the attention of the oil industry became focused on subsurface correlation, and field geology together with macropaleontology almost passed out of use. The development of micropaleontology in connection with the oil industry was so rapid and its success so immediate, that some fundamentals were almost of necessity neglected. At the start the microfaunas of most type localities were undescribed. It was quickly recognized that, for a producing area, a sequence of faunas could be established from the subsurface. Correlation was attempted with the surface units, but this could not be done to the satisfaction of everyone, until the micro-fossils at the type localities of the surface formations had been described.

* This paper and the two following papers were presented as parts of a symposium in the program of the Society of Economic Paleontologists and Mineralogists, Fort Worth, Texas, April, 1943.

[1] Synopsis of lectures in Paleontology 1, Univ. Calif. Press, Syllabus Series No. 20, 1910, p. 2.

Despite scores of very fine papers, there are many important surface formations whose type localities have not as yet been studied for their faunal content.

This meant that, at least for portions of the column, a new subsurface stratigraphic nomenclature was built up based on the sequence of the "tops" or upper ranges of certain species of foraminifera or other microorganisms. "Zones" in many cases were named for these species and an attempt was even made to subdivide certain surface units into formations on the basis of these "zones." In the Gulf Coast the problems of correlation between subsurface nomenclature and surface formations has been complicated by the fact that most of the marine units, on which our American Tertiary column is built, occur in Mississippi, Alabama and Florida, whereas, most of the subsurface "zonal" nomenclature has been developed for the area of coastal Texas, a state in which much of the Tertiary cropping out at the surface is non-marine or at best sparingly fossiliferous. Between these two areas and overlapping into both, lies the great deltaic accumulation of materials derived from the central portion of the continent.

It is only within the past decade that numerous deep wells have made possible an understanding of the complexity of the problems of zonation and correlation that are involved. Many of the problems would not have been realized and could not have been solved were it not for the development of electric logs. Electric logs have been as much help to paleontology as paleontology has been an aid in their interpretation. By means of these logs and with sections constructed from them, it can be definitely established that formations which are continental sands on the surface decrease in thickness and porosity and gradually merge into overlying and underlying marine clays in the subsurface. With a change in the character of sediments basinward, and with an accompanying change in environment, comes an extension of the ranges or "tops" of certain guide fossils. Or, in the case of other guide fossils, whose environment was shallow water and a sandy bottom, the change means their total absence. Or, in still other instances, faunas appear in the subsurface which are not represented on the surface at all.

Unconformities are geological datum planes and are caused by movement of the earth's crust. It is becoming increasingly common to report unconformities in the literature dealing with the Tertiary of the Gulf Coast. It seems to have been generally assumed that such movements need not have been due to folding in the immediate area but that any movement anywhere great enough to affect sea level would have a profound effect upon the position of the shoreline on so flat a coast as that of the Gulf of Mexico. In the areas marginal to the great deltaic accumulations of western Mississippi, Louisiana and eastern Texas, there appears to be a growing tendency on the part of geologists to assume an "unconformity" at every change from continental to marine or less frequently from marine to continental sediments. Without wishing to enter into a discussion of terminology, I feel that in some cases the proper term might better have been diastem, or rarely disconformity, but that most of the "breaks" merely represent a change in the direction of discharge of the major stream which drained the central portion of the continent. It should be recognized that the area where maximum sedimentation has taken place in the region of the Gulf Coast has changed from time to time during the Tertiary with very marked effect on the character of the sediments accumulating there and in regions adjacent thereto.

During Midway and Wilcox times the position of maximum sedimentation lay between western Mississippi and the east Texas syncline. The center of deposition shifted westward to the area south of the east Texas syncline during the Claiborne, Jackson and Vicksburg times. Since Vicksburg time the position of the center of maximum accumulation has shifted back and forth across southern Louisiana

apparently a number of times. Each of these shifts has produced interruptions in the sedimentary record or a change in the character of the sediments in adjacent areas. However, in the central portion of the Gulf Coast, I know of nothing in the sedimentary record which would indicate a complete cessation of sedimentation, or, it might be stated that there is nothing in the record which would indicate that sedimentation was not going on continuously during the Tertiary. The first great break in the record since Cretaceous time appears to coincide with the lowering of sea level during the glacial period, when it may well be that sediments were carried out well beyond our present shoreline.

It is a well known fact that the faunal associations of tidal streams, estuaries and beaches differ each from the other and that all differ from those living some distance off shore. It is likewise recognized that faunas differ laterally along the shore depending on such factors as the character of the bottom. Until detailed studies have been made of the ecologic units which comprise the present day fauna of the Gulf of Mexico, a full understanding of ecologic units encountered by wells in the subsurface section of the Gulf Coast is hardly possible. "From the biological standpoint the Gulf Coast is the least known marine area of the continental United States." A fine summary of what is known, however, has been prepared by Gordon Gunter. Not included in this summary, but of the utmost importance to the oil company paleontologist is the paper presented by S. W. Lowman at the Houston meeting of this Association in 1941. Similar profile studies should be made for the area of coastal Texas, and the areas east of the Mississippi delta. It would be most helpful in the latter area if the studies included all other organisms whose hard parts might be encountered as fossils, for many of our Tertiary limestones and limy clays contain vast quantities of recognizable parts of such organisms as ophiurans, comatulid crinoids, starfish, holothurians, bryozoa, etc., (Howe), organisms, whose presence would help to interpret the history of sedimentation.

On the assumption that the character of the sediments and the organisms which they contain have as much to do with the occurrence of petroleum as structures have to do with its concentration in commercial pools, I respectfully suggest the following conclusions. Because surface sections furnish, even in Florida, incomplete records of marine Tertiary sedimentation, the history of the region must of necessity be worked out in large part from the subsurface. To understand the subsurface record, cores should be studied from as complete a faunal standpoint as possible, rather than for foraminifera alone. Electric logs should be used to establish the sedimentary units from which each core was taken, and these in turn compared with similar records from other wells near by, and thence up dip to surface equivalents. It is only by working out a history of the sequence of environmental units that the full story of Gulf Coast sedimentation with the petroleum accumulations which it contains can be known.

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PALEOGEOGRAPHY AND PETROLEUM EXPLORATION

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ABSTRACT

Paleogeography in a broad way controls the deposition and distribution of source beds and reservoirs. The search for new deposits of petroleum is aided by the use of special paleogeographic maps. The term eulithogeography is introduced to cover distribution of favorable lithologic areas. Other types of maps that may be used show salinity, thickness of sands, paleogeology and paleotopography. All of these maps can be combined with structural contour maps to show depositional and post-depositional dips.

The three physical requirements for a commercial accumulation of petroleum are a source, a gathering system and a reservoir. In most petroliferous provinces possible reservoirs far outnumber the oil fields. As nature insures survival of the species by supplying more offspring than can possibly reach maturity, so are the stratigraphic sections supplied with more possible reservoirs than there is oil to fill them. Sheet sands, sand belts, porous limestones, buried hills and limestone reefs are some of the more common types.

Some possible reservoirs are not connected with source beds. Others are not closed or were not closed during the critical stages when oil was available. In other cases it is difficult to explain the "popcorn" porosity on closed structures. Likewise, a few source beds had no connection with gathering systems and reservoirs, or lost these connections before all the oil escaped. In other places the source beds were never rich enough to yield commercial oil. No one knows how numerous these unharvested sources are but presumably they are relatively common.

Gathering systems are freely permeable rock zones through which oil can migrate in spite of water saturation. The one type of gathering system not dependent upon paleogeography is the diastrophic fault-fracture system, which sometimes allows oil to accumulate where it would not otherwise be expected.

In almost every commercial oil field we find that the physical geography, ecology, structure and sedimentation are unitized. Optimum conditions for marine life occur in areas of agitation due to bottom irregularities. Irregularities in epicontinental seas mean shallow water. Currents moving over these shallows bring the cooler, food-bearing, bottom waters up into the zone of photosynthesis. Irregularities usually are either of structural origin, or they produce depositional or compactional structures in the overlying beds. If the topographic highs extend above sea level, they are attacked by erosion and either rendered more porous if made up of soluble rocks, or truncated to form porous wedges if the exposed section is composed in part of sandstones. Currents flowing along the shoreline or over the crests of the submerged hills concentrate the necessary coarse clastics for reservoirs and gathering systems, or if the shallow waters are warm and lime-saturated, they bring food for limestone-depositing organisms. The same currents that supply the coarse clastics and the food for both the lime-secreting and oil-forming organisms sweep the fine clastics and the dead organisms out into the deeps to wait for oil generation. This is the contribution of paleogeography to the formation and accumulation of petroleum.

The science of paleogeography was born when the foundations of stratigraphy were based upon a limited number of not too well known surface sections.

Early contributions to oil-finding were either negligible or even deleterious. Now with the number of borings on which we have accurate, dependable, stratigraphic information reaching into the hundreds of thousands, and with a much better command of the outcrop sections, we have a firm scientific basis for petroleum paleogeography. However, so numerous, extensive and unexpected have been the past geographic changes that we can seldom eliminate the "farmers sand" until a well reaches the basement.

For pools located on anything but the most obvious surface structures, it is difficult to determine the basis for picking the first successful location. Therefore, it seems more my place to suggest a few localities where paleogeography could have contributed to the finding of petroleum, rather than to tell how, where and by whom it was used. Certainly the science has added a number of tools, concepts and working hypotheses to the equipment of the petroleum geologist.

The best known of these tools is the conventional paleogeographic map. These maps can be used throughout the exploration and development program to give a general picture of geological and structural relationships to the non-technical management as well as to the geologists.

The main reasons that conventional paleogeographic maps are not used more extensively are that they take time to prepare and are never complete until development is finished. On most of them the units mapped are too large and they are based on age of the rocks rather than the all-important composition.

Lithology and sedimentary history are determined at the time of deposition and are as much products of geography as is original distribution. Besides they are the factors that control and limit production. So the first step is to work out the stratigraphy, from this to determine the favorable or eulithologic portions of the section, and then to map the eulithogeography. This is not simple because in many areas we do not know the stratigraphic expectancy. The Permian Basin with its upper salts and redbeds is a good example of a province that was condemned until the eulithology of the deeper formations was discovered.

On the Duval trend in South Texas it is not enough to know that Jackson beds are present but it is necessary to know the distribution of the permeable Jackson sands. Likewise, in the South Tampico area, the Cretaceous Tamaulipas formation underlies the whole district but it is only the El Abra facies that brings smiles to the production men.

Sometimes the eulithogeographic data are really mapped; at other times they are used without being formally plotted, and that is why concepts and working hypotheses were included above as exploration equipment. The eulithogeologic map might well be called a fairway map with many wells still being drilled in the rough. This is fortunate because wild wildcats still contribute much important geological data.

A modified lithogeographic map frequently used is the lithologic isopach. Citing Duval County again, the productive possibilities vary directly with the total amount of sand in the Jackson section. In some parts of the mid-continent, isopach maps showing the amount of limestone in a given section are as valuable as structure maps. Limestone loves shallow water and the shallowest water usually occurs over submerged structural highs. Thus a limestone isopach map would point out the Cement pool in south central Oklahoma as a very likely prospect even if the surface structure were not apparent.

Compound maps showing structural trends on an eulithogeographic base are extremely useful. They really tell which structures are in the fairway. As long as the lithology is favorable, the trend can be followed with confidence that tests drilled will give a run for the money. In cases where oil is abundant enough to overflow the local structural traps,

lithogeography is more important than structure.

Sedimentary trends, like the shoestring sands of Kansas and the limestone reefs of the Permian Basin, tend to make their own structures. In both cases the relative uncompressibility of the porous rock causes dips in the overlying strata. It makes little difference whether the limestone highs are reefs or limestone islands or whether the sands are bars or rows of sand dunes.

The approximate location of narrow porous trends that are known to exist in parts of the section, can frequently be determined by a careful stratigraphic analysis of the dry holes in the area. Productive porosity is largely limited to shallow water or to subareal deposits. Deep water limestones are usually dense and almost impervious and most of them are dark colored. Dense shallow water limestones are more often white. Porous zones, when present, come between the dense white and the dense dark areas or within the dense white areas. Deep-water clastics are represented by silts, shales and silty or shaley sandstones. On the up-dip edge of the porous sand zone, the productive sands are usually missing due to truncation, overlap or shoreward gradation. In the past it has usually been too much of a job to search the section for all of these possible porous zones and only those accidentally found productive have been worked out. Another excuse for not doing this work is that in many areas stratigraphic information is not sufficiently detailed to carry it through successfully.

Diastrophism cannot be left out completely. Mashing of the earth's crust puts widely separated depositional facies in juxtaposition and sometimes links source beds to reservoirs. Plastic paleogeographic maps that pull the section back into its proper depositional distribution sometimes clear up the problem. Very little work has been done with this type of map but a few areas that would normally be condemned have been opened for exploration by their use.

Fossils and sediments usually reflect the salinity of the water in which they were deposited. From these data salinity maps can be drawn. Some oils may have originated in fresh water deposits but so far little search has been made for non-marine petroleum.

Brackish water is normally less densely populated than marine water and the oil in brackish deposits is seldom as prolific as in true marine sediments. The line between brackish and marine areas may be very sharp but it tends to fluctuate and the deposits frequently overlap. The Wilcox of the Gulf Coast was long regarded as a brackish deposit and not rated highly as a petroliferous prospect, but wells have shown that marine sediments start a short distance from the outcrop.

Excessive salinity inhibits life even before calcium sulphate precipitation concentration is reached. Many primary dolomites are very low in fossil content but the barrier zones in barred saline basins are frequently sought because of their structural position and because of the killing and preserving effect of the brines within the basins.

Lack of circulation and a consequent deficiency in oxygen tends to produce black shales. In some areas, as in the Comanchean section of the Rio Grande Embayment, excessive evaporation accompanies lack of circulation. Anhydrite and even salt may thus be mixed with the black shales. Black shales are not necessarily good source rocks. It is true that most of the organic matter is preserved but the lack of bottom dwellers cuts down on the amount of available organic matter and the lack of currents to distribute the coarse clastics necessary for a gathering system cuts down on the oil harvest except along the margins.

Paleogeologic maps, as the name implies, show the areal geology of some period in the past. They are used most extensively in mapping the sole of an un-

conformity and in outlining the distribution of porous beds, and are especially useful in locating and developing production around "bald-headed" structures. These maps are geographical inasmuch as paleogeography was largely dependent upon paleogeology.

Paleotopography of an overlapped unconformity is frequently as important as the paleo-areal geology. Limestones and other soluble rocks produce from buried hills. Examples are the Ellenburger production at KMA in North Texas, the Arbuckle production at Oklahoma City, the Mississippian chat production in Kansas and the serpentine plugs of the San Antonio district.

Topography on an unconformable surface also tends to control production in the overlying section. Hills and buttress ridges thin or completely cut out flank sands. East Texas is a good example. Depositional and compaction dips, developed over the topographic highs during and after burial trap oil in many pools. In West Texas, the submarine and subareal topography of the pre-Permian surface was directly responsible for the initiation and location of the Permian reefs. Most paleotopographic maps pass under the name of structural maps but there is a distinct difference.

Although the topography of an overlapped unconformity is important, the topography of a coastal area is secondary. Major streams frequently bring in coarse material across wide coastal flats and currents distribute this material along the flat bottoms. If there are no coarse clastics, porous limestones may develop to take their place. Granite wash of the Panhandle type is possible only where the shore line is backed up by a granite ridge, but granite wash is just another coarse clastic. Almost any other material of similar size grade would serve as well. Besides, oil in the Panhandle is produced from the associated limestones as well as from the wash.

Other paleogeographic features could be mapped but it is believed that the maps listed above cover most of the commonly used and practical paleogeographic contributions.

While the term "map" is used above, it should be understood that many of the features are best shown on cross sections. Some geologists are so familiar with the areas in which they work that they use and interpret paleogeographic data without formally plotting them.

CONCLUSIONS

Paleogeographic methods are most effective in sedimentary basins showing differential subsidence, widespread unconformities and horizontal variations in sedimentation. Where these basins are filled largely with marine sediments, they are natural petroliferous provinces.

Effective use of paleogeography in locating or extending deposits of petroleum requires an extensive knowledge of province stratigraphy. Modern subsurface methods furnish much of the necessary information. Both deep, off-structure wildcats and field wells are important.

Paleogeography can seldom be used to find oil in widespread sheet formations. Neither is it especially useful in locating fracture-type reservoirs. Those are problems for the structural geologist. Oil found by paleogeography will occur as high on the local structure as open porosity will permit. The main thing to be remembered is that paleogeography, although a science in itself, is just one of the supplementary tools used in petroleum geology.

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AID OF SEDIMENTARY PETROLOGY TO THE DISCOVERY OF OIL

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ABSTRACT

The importance of sedimentary petrology to the discovery of oil is reflected in its wide utilization by the oil companies. It is the source of numerous criteria which constitute the basis for subsurface correlation. The study of sediments is considered paramount for the determination of porosity, for successful acidizing, and for information that can be used at the time of drilling.

INTRODUCTION

The importance of sedimentary petrology in exploration for petroleum has undergone several stages. The first stage includes the time prior to and including the era of the drillers' log. This record was prepared by the driller, or a member of the drilling crew who examined and classified the materials. Often the driller's knowledge of sediments was limited and regardless of the type of material it was classified as "lime," "sand" or "clay." Since preparing the log was an additional duty, often considered unnecessary, it did not always give an accurate representation of the sedimentary sequence. Even though discrepancies occurred, the drillers' log was an important contribution to sedimentary petrology. It provided an early method for subsurface correlation and also served as an impetus for additional and a more accurate study of subsurface sediments.

The second stage in the development of sedimentary petrology was probably the result of a sharp increase in the consumption of petroleum products. In order to supply the increased demand it was necessary for the oil companies to expand their holdings and to increase production. The inadequacy of the drillers log led to improved methods for the study of sediments which included greater care in the collection of well cuttings, the development of sedimentation laboratories, and the training of men for sediment study. After the well cuttings had been collected they were assembled usually by a scout who was responsible for their delivery to the central or regional office. In the laboratory each sample received special consideration. It was carefully examined and the classified materials were later recorded on well strips. During this stage sedimentary petrology contributed the major part of the information that was utilized in the discovery of oil.

The third and present stage in the development of sedimentary petrology was ushered in during a period of flush production which resulted in a huge oil reserve and a decrease in the price of crude. These factors combined with the desire on the part of the oil companies to decrease the cost of production were in part responsible for a more complete development of sedimentary research. A part of this research was under the auspices of the oil companies but no doubt individuals working on special problems were chiefly responsible for its development. Research has been aided by special funds appropriated for that purpose and by the cooperative attitude on the part of the oil companies which included the imparting of information and the pooling of well cuttings from which all producers who desired could receive a cut.

IMPORTANCE OF SEDIMENTARY PETROLOGY

The significance of sedimentary petrology in the exploitation of petroleum is reflected in the army of workers who are directly or indirectly occupied with sediments. So far as known, no estimate as to

the number is available but in each regional office one to five are actively engaged in the accumulation and compilation of sedimentational data. This information is utilized as an aid to the discovery of petroleum among which correlation, determination of porosity, acidizing, drilling activities, and the solving of petroleum problems are of major importance.

CORRELATION

It has long been recognized that correlation by subsurface methods is of major significance in the discovery of oil. This objective was no doubt responsible for the extended utilization of well cuttings by oil producers. From sediments, numerous criteria which constitute the basis for correlation have developed. Among these horizon markers, insoluble residues, heavy mineral assemblages, volcanic ash, fossils and color of sediments are considered primary.

Horizon markers.—Perhaps the first and still the most widely used correlation method is generally known as picking points or horizon markers. These markers usually consist of a change in lithology or a break in deposition. Most oil fields are characterized by definite horizon markers some of which have a wide horizontal distribution extending not only throughout the producing area but into adjoining regions. In the Hobbs field, New Mexico, the top of the anhydrite, the brown lime, and the top of the "Big Lime," constitute the chief basis for correlation. In the Jal area, New Mexico, about 75 miles south of Hobbs, the horizon markers, in addition to the top of the anhydrite and the top of the "Big Lime," include the Yates Sand. In some areas correlation based on horizon markers has proven satisfactory, but in others difficulties have been encountered. When used alone this one criterion is not always a dependable basis for correlation.

Insoluble residues.—Insoluble residues consist of materials that are not readily affected by hydrochloric acid. Correlation by insoluble residues is a recent advancement in sedimentary petrology. Its development is primarily the result of research by individuals not directly connected with oil discovery. However, several oil companies have developed and still maintain well equipped insoluble residue laboratories. In some areas, especially where thick unfossiliferous limestones or dolomites occur, correlation is simplified by the utilization of insoluble residues. Ireland in his work with insoluble residues included the characteristics of the materials and their abundance as a basis for correlating limestone formations in Oklahoma. Cole used several varieties of chert as a basis for subdividing the Ellenberger formation of West Texas into zones. In Terry County, West Texas, the insoluble residues in the "Big Lime" consist of a few heavy minerals, gypsum, quartz crystals and organic materials. No doubt with additional study they could be used as a basis for correlation. The utilization of insoluble residues is largely restricted to calcareous formations.

Mineral assemblages.—Even though the use of mineral assemblages, due to the time required for preparation, is curtailed in oil discovery yet their significance by the oil companies as well as research workers is generally recognized. The flexibility in the use of mineral assemblages is an additional advantage for correlation. Some of the better known methods are summarized.

1. *Grouping.*—The minerals from a definite horizon are separated into two or more groups, each characterized by one or more minerals. Milner divided the minerals secured from the Sante Fe Springs Field, Los Angeles, into two groups, one characterized by the abundance of green hornblende, the other by epidote, pyroxene and no hornblende.

2. *General analysis of sediments.*—A detailed analysis of sediments often reveals a heavy mineral assemblage associated with other materials as rounded quartz grains or organic fragments. Such

an associated assemblage is often utilized in the identification of a specific horizon.

3. *Index minerals.*—Adjoining horizons are identified by one or more mineral species which may be abundant in one zone and absent in the other. It is not unusual for minerals to be present that are common to both horizons. Tickel differentiated the Eocene and Miocene, Ventura County, California, by the abundance of amphiboles in the Miocene and by its absence in the Eocene.

4. *Physical properties of minerals.*—Trowbridge and Mortimore on the basis of physical properties of minerals correlated the Wilcox, Hominy, Bartlettsville and Elgin formations of Oklahoma. They stressed the value of angularity, roundness and size of the mineral grains.

5. *Special features of minerals.*—Features as well preserved crystals, inclusions, faceting and twinning not only aid in correlation but provide suggestions as to the character of the former terrain. The variation in the type and composition of inclusions, as crystals, bubbles, or needle-like forms, is often considered conclusive in respect to the identification of horizons. They also give a clue as to the origin of the mineral.

6. *Physical features of minerals.*—Physical features of minerals, as color, luster, shape and external form, provide a good criterion for correlation. Color of minerals may be uniform, patchy or parti-colored. In some mineral species, variation in color from the ordinary not only indicates a different condition of origin, but it usually constitutes a marker for identification. External form refers to the structure of the mineral grain as fibrous or crystalline. The occurrence of fibrous hornblende, actinolite, may identify a specific zone.

7. *Optical properties.*—Unusual optical properties in respect to pleochroism, refractive index, birefringence or interference figures, are important identification markers. Variation in pleochroism from the normal, which may occur in some tourmalines, is readily noted and it often constitutes a distinctive feature.

8. *Authigenic minerals.*—Authigenic minerals, as pyrite, gypsum, leucoxene, quartz and others, are formed within the sediments either contemporaneous with or following their deposition. When present these minerals give some indication as to the environment of deposition. They are now used in central and south Texas to ascertain the relative position of the oil producing horizons.

Volcanic ash.—The occurrence of volcanic ash is probably more widespread than is generally believed. It occurs as distinct beds or as disseminated materials that are associated with other sediments. Volcanic ash even when altered contains distinctive materials that may be utilized in the identification of specific horizons. Unaltered volcanic ash is usually porous, light in weight, and contains glass shards, whereas the altered materials possess bentonitic properties and characteristic clay minerals. The use of volcanic ash for correlation has been limited but with more detailed sedimentary work it may become an important identification marker.

Fossils.—Supporting structures of plants and animals are an important source of sediments. In the discovery of oil, shells of microscopic animals and reef materials are important aids. Reef materials are also of value for locating former shore lines. Also, in some areas oil reserves are associated with reefs. Shells of microscopic animals, where sufficiently abundant, are used as a basis for horizon identification. For subsurface correlation, fossil assemblages as well as index forms are commonly used. Fossil assemblages consist of several associated species that occur in a specific horizon. Index forms include one or more species that are characteristic of a definite horizon. Sedimentary formations in some regions, as in portions of the Gulf Coastal plain, can be correlated over a wide area on the basis of fossils. However, in a few

localities, as in Permian deposits of West Texas, fossils are not present in sufficient numbers for general use.

Rhythms in deposition.—In many areas rhythmic changes in deposits are indicated by the general sequence of materials. Alternation of sediments within a deposit, as coarse materials with finer, beds of limestones with shales, or a group of beds with another group, often suggests cycles of deposition. Rhythms in sediments (Twenhofel) may result from any of the following causes: weather changes, seasonal changes, climatic changes and diastrophic changes. It seems probable that rhythms caused by weather or seasonal changes would be restricted whereas those caused by climatic or diastrophic changes cover a much wider range. The use of rhythms in sediments for the discovery of oil has been limited. Hills in a recent article outlined the physical history of the Permian in the Delaware Basin on the basis of paleogeographic evidence. It is probable that rhythms could be more fully utilized especially in research work relative to oil discovery.

Other criteria.—Color of sediments, type of cementing materials, thin sections, chemical composition of sediments, replacement products and others often constitute a basis for correlation. Of these the first two are briefly discussed. The color of sediments may provide evidence concerning the parent rock and conditions of deposition yet its use for correlation has limitations. Color of materials in a formation may undergo an abrupt change either vertically or horizontally within a short distance. For correlation color of sediments is valuable when used with other criteria.

The common cementing materials are quartz, limonite and calcite. Cementing materials that are unusual in respect to composition or texture are sometimes valuable as horizon markers. Some sandstones are readily identified by the type and character of the cementing materials.

IMPORTANCE OF CORRELATION

The value of subsurface correlation to the discovery of petroleum is difficult to evaluate, yet it is of primary importance in oil exploitation and production. Some of the results are summarized.

1. The horizontal distribution and thickness of oil producing horizons is determined by subsurface methods. The Yates Sand is of considerable thickness and a producing horizon in southeastern New Mexico and parts of West Texas but it thins to the north and finally wedges out.

2. The approximate depth of the producing horizon can be ascertained. This permits the use of precautions which prevent waste of petroleum products, the destruction of property or even the loss of life.

3. Correlation aids in securing a survey of geologic structures which includes the trend, size and extent of closure. This information is valuable in locating new wells and in securing an estimate of the potential production.

4. The change of facies in a member or formation, from reef to neritic, or marginal to neritic, is generally recognized by subsurface correlation methods. Since change of facies usually involves a change in sediments, it is useful in the location of oil producing horizons.

POROSITY

Porosity is (Krumbein and Pettijohn) percentage of pore space compared to the total volume of the rock. The sedimentary factors controlling porosity (Fraser) are size of the grains, shape of the grains, method of deposition, compaction, and solidification. Ordinarilly, it is the sedimentary petrologist who evaluates the above factors in order to determine the degree of porosity. During the preparation of the percentage log, porosity if it appears in the section, is estimated as good, medium or poor. Since porosity is one of the controlling factors

in primary as well as secondary recovery, emphasis in recent years has been placed on this phase of sedimentary petrology.

ACIDIZING

Acidizing is the process (Love and Fitzgerald) of introducing hydrochloric acid into limestone formations to enlarge the pores and extend them into new drainage areas. For the acidizing process to be successful geological factors as chemical composition of the beds, porosity, permeability, stratigraphy, structure and physical characteristics, must be considered. Since a study of sediments is the chief source for this information and successful acidizing is a means of increasing production, sedimentary petrology is in a measure responsible for the increased recovery.

DRILLING OPERATIONS

Utilization of sediments is one of the basic methods employed by oil companies to keep informed concerning drilling operations. Drilling in proven areas uses sedimentary petrology to secure information relative to:—position of the structure, if high or low; the horizons that show porosity; zones that can be successfully acidized; and the lithologic changes that occur in the section. From these data the approximate location of the pay section and the position of any promising oil horizons can be determined.

It is sometimes customary for oil companies in unproven areas to place a sedimentary petrologist on the location. By examining the samples on the ground he has at hand valuable data which constitute the basis for recommendations concerning drilling and recovery methods. Even though it requires all of one employee's time, it is no doubt an economic measure.

CONCLUSIONS

No effort was made to compile a comprehensive report but merely to summarize some of the important contributions of sedimentary petrology to the discovery of petroleum. No doubt some of the methods presented are not particularly applicable to the oil man as they require considerable time for preparation and study. However, since oil is an irreplaceable commodity and it is generally recognized that in time the supply will be greatly depleted the use of all available methods for the discovery of petroleum should be utilized.

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FIGS. 1–2, TABLE 1, DECEMBER, 1943

AN EXPERIMENTAL STUDY OF THE INFLUENCE OF GRAIN-SIZE ON THE SIZE OF OSCILLATION RIPPLE MARK*

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ABSTRACT

Wave-tank experiments show that with an increase of grain-size of well-sorted sands the oscillation ripple marks that form on them increase in both wave-length and wave-height, and that with a half-and-half mixture of two well-sorted sands the ripple marks are smaller in both wave-length and wave-height than the ripple marks that form on either of the two sands when rippled alone.

INTRODUCTION

Factors that determine the size of oscillation ripple mark include wave-size; depth of water; size, sorting, shape, and density of the grains; and perhaps others. In the field it is almost impossible to separate the effects of these various factors since there are too many variable unknowns, and therefore laboratory study with control over these factors is necessary in order to determine the effect of each of the above factors on the size of oscillation ripple mark.

Little experimental work has been done in trying to separate these factors. Until the work of Evans in 1942 on the effect of wave-size and depth of water on the size of oscillation ripple mark, the experiments of two contemporary Frenchmen, Forel (1883) and de Dandolle (1883), in the latter part of the nineteenth century stand alone in the study of the causal factors of the size of oscillation ripple mark. Forel and de Candolle did excellent work of the kind that is needed; but since their work was done in the early days of the study of ripple marks when data on ripple marks and ocean waves was not as complete as it is today, it is natural that some of their explanations may be questioned.

The only original investigation of the influence of grain-size on the size of oscillation ripple mark was that done by Forel and de Candolle. From experiments in a pendulum-oscillating tank and observations in Lake Geneva, they concluded that the wave-length of a ripple mark is the distance a grain of sand, freely transported by the water, moves in a forward movement of the water particles in an oscillation wave, this distance being proportional to the amplitude and velocity of water particle motion and inversely proportional to the density and the *size of the grains.*

Contrary to these conclusions, the wave-length was found to increase as larger sands were used, this being explained by de Candolle (1883), p. 255 in the following way:

> It is clear, that for the same kind of material, the larger grains, being the heavier, require a greater movement of the water in order to be moved than for the finer grains. The larger grains then can only produce ripple-marks corresponding to a considerable amplitude of oscillation, and therefore the ripple-marks are wider spaced and at the same time deeper than those formed on the finer sands.

Thus it appears that the law that Johnson (1919) and Bucher (1919) quote from Forel—that the wave-length of ripple marks is directly proportional to grain-size—necessitates larger waves for the larger grains; and that if only one size wave were present, the results would be directly opposite, the larger grains pro-

* This study was presented as a thesis for the degree of Master of Science at the University of Oklahoma in 1943 by Roy L. Ingram.

ducing the smaller ripple marks. The work of the writers gives an opposite result.

From theoretical considerations, Forel also concludes that in sands, where grains of different sizes are mixed, it is probable that the largest grains will determine the size of the ripple marks; that is, large ripple marks will form corresponding to the larger sand grains. The work of the writers give a different result.

The explanation of Forel and de Candolle is confusing because of the lack of control of the various factors that control the size of ripple marks.

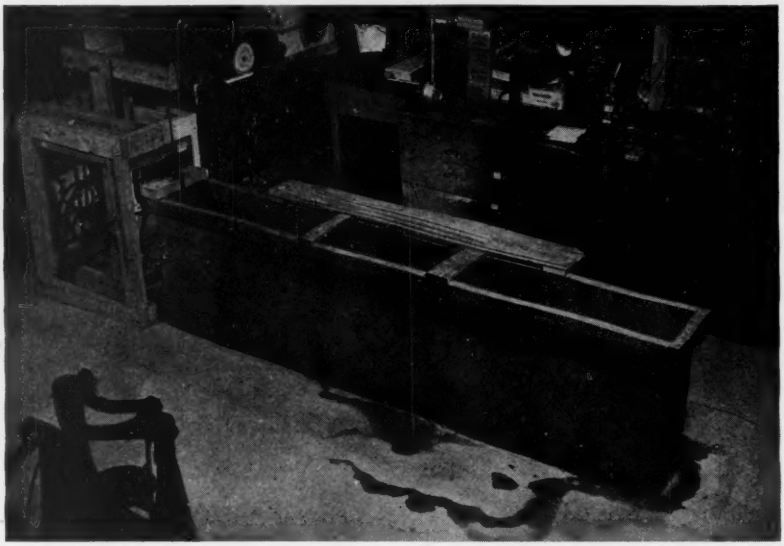

FIG. 1.—Apparatus used in making the ripple marks.

APPARATUS AND PROCEDURE

Sub-angular to sub-rounded quartz sand from the flood-plain of the Canadian River south of Norman, Oklahoma, were screened, obtaining five very well-sorted sands with median diameters of 0.08, 0.15, 0.24, 0.44, and 0.57 mm. A sixth grade of sand was obtained by mixing the 0.08 and 0.44 mm. sands in equal volumes, giving a median diameter of 0.20 mm. A layer, 4 cm. thick, of each of these sands was rippled in a galvanized-iron wave-tank (see Fig. 1) 2.4 m. long, 0.25 m. wide, and 0.64 m. high, with the waves being generated by the up-and-down movement of a right-angle triangular-prism plunger whose generating face made a 40° angle with the vertical. The up-and-down movement was provided by a walking-beam connected to a 1725 r.p.m. motor through a reduction pulley.

The wave-length of the generated waves varies inversely as the plunger frequency; the wave-height varies directly as the plunger frequency and the plunger amplitude while the plunger is in the water. Using a fixed plunger amplitude, which was held constant throughout the entire experiment, the sands were rippled by two different wave-sizes (ob-

tained by changing the plunger frequency) in water 15 cm. deep.

After each of the sand sizes was rippled the water was drained from the tank; and the wave-length of as large a number of ripple-marks as possible measured with a meter stick. Since the sand was too soft to withstand much pressure, the wave-height could not be measured directly. Moulds of the ripple marks were made by pressing a galvanized-iron frame into the sand and sifting moulding plaster into the frame to a thickness of about 3 cm. Water was sprinkled on the moulding plaster until the plaster was thoroughly wet. After setting for about 45 minutes, the mould was removed and the wave-height measured directly from the mould.

Table 1 summarizes the experimental data collected.

With increasing grain-size, all other factors remaining constant, there is an increase in both wave-length and wave-height.

The ripple marks that form on the half-and-half mixture of the 0.08 and 0.44 mm. diameter sands are smaller in both wave-length and wave-height than the ripple marks that form on either of the two sands when rippled alone.

Bucher (1919, p. 161) gives a theory which may explain the observed results. Oscillation ripple marks form essentially by the superposition of two current ripple marks facing in opposite directions so that reasoning that applies to the formation of current ripple marks can be applied to oscillation ripple marks with only slight modification. Experiments with the flow of water over inclined weirs (see Fig. 2) show that as the velocity of flow over the weir decreases there must be a corresponding decrease in the angle of slope, A, in order to maintain a maximum discharge. Ripple marks act as weirs in a stream. With the coarser sands making up the ripple marks, there will be more friction between the sand and the water than with the finer sands. This increase in friction causes a decrease in the velocity of flow, with the decrease in velocity causing the angle that the upstream face of the ripple mark makes with the horizontal to decrease in order to maintain a

RESULTS

TABLE 1.—*Summary of data**

Grain-Size	Water Wave		Ripple Marks	
Median Diameter mm.	Wave-Length cm.	Wave-Height cm.	Wave-Length cm.	Wave-Height cm.
0.08	160	3.5	4.35	0.79
0.15			4.74	0.86
0.24			5.77	1.00
0.44			6.10	1.00
0.57			No Ripple Marks	
0.08	100	4.0	2.66	0.50
0.15			3.05	0.55
0.24			3.20	0.57
0.44			No Ripple Marks	
0.20	160	3.5	3.84	0.61
(Half-and-half mixture of 0.08 and 0.44 mm. diam. sands)	100	4.0	No Ripple Marks	

* Each set of measurements represents the average of several experimental runs.

maximum discharge. This decrease in the slope can be explained by an increase in wave-length *in spite of* an increase in wave-height.

With a mixture of large and small grains, the surface will be smoother than with either the large or small grains alone since the small grains will tend to fill in the spaces between the large grains. This smooth surface will cause a higher velocity and a corresponding increase in the angle of slope of the ripple mark face. This increase can be explained by a decrease in wave-length *in spite of* a decrease in wave-height. With different mixtures different results may be obtained, and it is entirely possible that in a mixture where the larger grains greatly predominate the ripple marks formed may be controlled by the larger grains as Forel and de Candolle believe. Further work needs to be done on the effects of sorting.

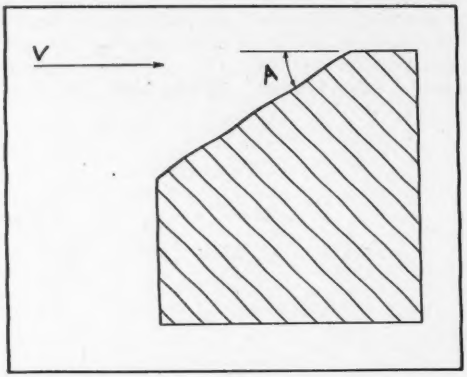

FIG. 2.—With flow over an inclined weir the angle, *A*, that gives a maximum discharge decreases as the velocity of flow, *V*, decreases.

The data in these experiments are not accurate enough to allow accurate computations of the slope angle of the ripple mark faces to see exactly how the slope changes.

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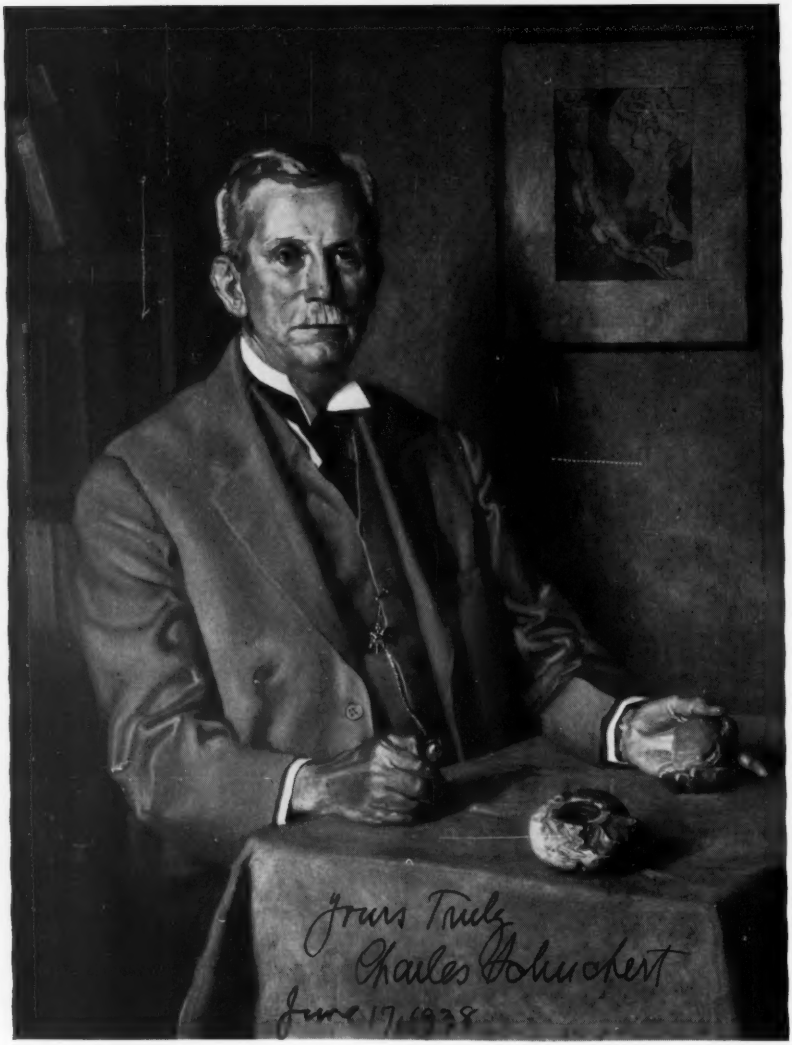
Yours Truly
Charles Schuchert
June 17, 1938

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 13, NO. 3, PP. 121–129
FIG. 1, DECEMBER, 1943

MEMORIAL TO PROFESSOR CHARLES SCHUCHERT (1858-1942)

The American Association of Petroleum Geologists lost its most eminent member on November 20, 1942, with the passing of Professor Charles Schuchert, Emeritus Professor of Paleontology in Yale University and of Historical Geology in the Sheffield Scientific School.

Professor Schuchert was born of German parentage in the city of Cincinnati on July 3, 1858. His parents came to the United States in the wave of German emigrants who left Germany in the middle of the nineteenth century to seek fortunes in the New World and at the same time to escape the pressure of the dead hand of dictatorial government of the land of their birth. The coming of these people enriched the United States and some of the brightest minds in science, art, literature, government and business were outcomes of their coming. Professor Schuchert's stock is that of western Germany. His father, Philip Schuchert, came from Hesse on the Rhine and his mother, Agatha Muller, from Franconia. Philip Schuchert engaged in the manufacture of furniture and it seemed that the boy, Charles, would follow in his father's footsteps.

Charles Schuchert left school at the age of 13, and, except for a part of a year's work in a business college in the following year, his formal education ended with the equivalent of about the sixth grade. Leaving school he went to work in his father's business—he had worked there when attending school—in which he continued until 1884 when at the age of 26 a fire reduced the buildings to ashes. This event changed the course in his life. The writer knows little of his boyhood activities except as gathered from conversation with Professor Schuchert himself. He told of his interest in singing and his hobby of collecting and studying fossils. At one time he was a member of a singing society, a characteristic activity found in many strongly German communities. This society made visits to other cities to sing, and on one trip went as far as St. Louis, another city with a large German element. Anyone knowing only the later life of Professor Schuchert would not have been likely to suspect this interest. The writer has never seen or heard him sing.

The region about Cincinnati fulfills a paleontologist's idea of Paradise. The hills about the city expose alternating beds of shale and limestone, each once the bottom of a sea, with almost every bed containing beautifully preserved fossils. Ascent from the level of the Ohio River takes one from the Trenton to high up in the Cincinnatian series and not far distant from the city to the highest strata of the Ordovician system. Charles Schuchert's first fossil was obtained by him at the age of 6 when a workman in a ditch tossed him a horn coral, probably *Streptelasma corniculum*, and told him it was the horn of a nannie goat. As he grew in years he found his own fossils. Each fair weekend congenial souls gathered at some designated rendezvous, perhaps the drugstore of U. P. James, for a collecting trip into the hills in search of fossils. It was a gathering of men and boys of many lines of interest. Golf was then unknown about Cincinnati and fossil hunting took the place of golf. Some Cincinnatian should assemble this history for the interest of future geologists and also Cincinnatians. Ultimately Schuchert's interests took him to the museum and meetings of the Cincinnati Society of Natural History and there he made the acquaintance of E. O. Ulrich, curator of that museum from 1877 to 1881. They immediately became firm friends. Ulrich had had the advantage of some collegiate training, first in theology and later in medicine, and was thus better equipped for the study of fossils than the young Charles Schuchert. Schuchert was an apt pupil and in 1885, in his 27th year, he became

an assistant to Ulrich and remained with him until 1888, doing work in Ohio and Illinois.

Professor Schuchert seems early to have decided to make the study of brachiopods his specialty and to learn all that he could of the group. To this end he made large collections from the rocks of his native hills, exchanged specimens where this could be done, purchased specimens otherwise not obtainable, studied the available but scanty literature (chiefly volume 1 of the Paleontology of Ohio), spent much of his spare time studying and arranging his specimens, and played with his collections as boys of today play with their collections of stamps. James Hall, the eminent State Geologist of New York, ultimately heard of him, and he left Cincinnati in 1888 to become Hall's assistant. The wages were small but the opportunity was great, as Hall was then the leading paleontologist of the New World and the New York Survey possessed the largest collection of fossils in the United States and one of the best libraries of geology in the New World. He published his first paper in 1889 while with Hall. It had the title, "A List of Fossils Occurring in the Oriskany Sandstone of Maryland, New York and Ontario." He remained with Hall until 1891, when he left to become a member of the Geological Survey of Minnesota. Professor Schuchert seemed rather fond of reminiscing of these years with Hall, and frequently related anecdotes in which Hall was the chief actor. While a great admirer of Hall, he does not seem to have developed any particular fondness for him. These three years were fruitful as he learned much of method from his chief, widened his knowledge, read widely from the books which Hall had assembled and became familiar with New York stratigraphy.

His work with the Geological Survey of Minnesota led to the publication, with N. H. Winchell, of his papers on, "The Lower Silurian Brachiopoda of Minnesota," and "Sponges, Graptolites, and Corals from the Lower Silurian of Minnesota," both published in 1895 as parts of the Volume 3, pt. 1, of the Minnesota Geological Survey. He had previously published in collaboration with N. H. Winchell, "Preliminary Descriptions of New Brachiopoda from the Trenton and Hudson River Groups of Minnesota" in Volume 9 of the *American Geologist*, 1892. This last paper and a paper on "A Classification of the Brachiopoda" in 1893 (Vol. 11, *American Geologist*), mark Schuchert's entrance into the field in which he was destined to become an authority.

He left the Minnesota Survey in 1892 to become an assistant to Professor Charles Emerson Beecher of Yale University. This marks another prominent point in his life as it placed him under the tutelage of perhaps the most outstanding teacher of paleontology of his time. He was permitted to assist in Beecher's studies of brachiopod ontogeny and phylogeny. His work was that of preparator and his two years with Beecher led to the preparation of some of the finest slabs of invertebrate fossils in the Yale Collection. The work shown on these slabs testifies to the meticulous and almost loving care he bestowed upon them. It is doubtful if at that time his thoughts ever soared to the possibility of his becoming Beecher's successor.

He was called to Washington in 1893 as an assistant paleontologist of the United States Geological Survey from which position he went in 1894 to become Assistant Curator of Stratigraphic Paleontology in the United National Museum, in charge of the Paleozoic Invertebrates. While holding this position he published his "A Synopsis of American Fossil Brachiopoda, Including Bibliography and Synonymy" (1897). This paper brought to some degree of fruition the work begun in his boyhood—his determination to master all that was known of the Brachipoda—and placed him among the foremost students of this group of invertebrates. Three years later (1900) he published the chapter on the Brachiopoda in the Eastman-Zittell "*Textbook of*

Paleontology," the standard English work of the day on paleontology. In 1902, in collaboration with Doctor E. O. Ulrich, he entered the lists in the complicated problems of Appalachian paleogeography in their paper on "Paleozoic Seas and Barriers in Eastern North America." Professor Schuchert lived to repudiate much that was postulated in this paper.

The work in the National Museum extended over ten years. It widened Schuchert's experience, reading, perspective and knowledge. During this period some twenty-five papers were published. Among them was one in 1894 on, "Directions for Collecting and Preserving Fossils." Anything better in this field, so far as invertebrate fossils are concerned, has yet to be written. He and David White were with Peary in Greenland in 1897 and they made collections of fossil fish and invertebrates and fossil plants from Cretaceous and Cenozoic strata in the vicinity of Disco Island in western Greenland. He worked in Wyoming in 1899 as a member of an expedition sponsored by the Union Pacific Railroad which had as its objective the publicizing of the strata containing the giant Jurassic reptiles, the largest land animals of all time.

His first opportunity to go abroad came in 1903 when he attended the meetings of the International Geological Congress in Vienna as the delegate of the United States National Museum. He took advantage of this opportunity to become acquainted with the geology of, and with the collections from the Cambrian and Ordovician strata of the then Baltic area of Russia. He also traveled in England where he made the acquaintance of F. A. Bather and other geologists. He was invited to Dr. Bather's home for dinner. Celery was on the table in some sort of vase. In the United States this is intended to be eaten as an appetizer. Schuchert naturally assumed that such was the case in England and he was greatly chagrined later to learn that he had eaten of the table decorations.

He was called to Yale in 1904 as the successor of Professor Beecher whom he succeeded as Curator of the Geological Collections of Peabody Museum and Professor of Paleontology in Yale University and of Historical Geology in the Sheffield Scientific School. This is the sequel to a typical Horatio Alger story in real life. He was the third to hold the curatorship, the first was O. C. Marsh, the second, C. E. Beecher.

The most fruitful period of Professor Schuchert's life began with this appointment. He was 46 years of age, active, enthusiastic to learn, in good health, and keen to make the most of his position and to be of service. The brachiopod collection, now greatly enlarged through collection, exchange, and purchase, came with him to Yale. It was then and for a long time afterward, and perhaps is still today, the finest and best collection of brachiopods in the world and certainly in North America. Two fundamental papers on the Brachiopoda ultimately stemmed from this collection. The first, published in 1929, was prepared by Professor Schuchert with the assistance of his secretary, Miss Clara Mae LeVene. It is a catalogue with bibliography of all brachiopod genera and genotypes. The second, prepared with the collaboration of Doctor G. Arthur Cooper, was published in 1932 and presents a revision of the genera of the two brachiopod suborders of Orthoidea and Pentameroidea (Brachiopod Genera of the Suborders Orthoidea and Pentameroidea, volume 4, part 1, of the *Memoirs of the Peabody Museum of Natural History*).

Professor Schuchert's scientific fields of research were in stratigraphy, paleontology, and paleogeography. He was deeply concerned with the lower Paleozoic—of the stratigraphy of the Cambrian, Ordovician, Silurian, and Devonian systems. His interest after 1900 centered to a considerable extent in eastern Canada. He visited Gaspe and the Silurian section of Arisaig, Nova Scotia, in 1900 in company with Doctor John M. Clarke, the then State Geologist of New York. He stayed at Arisaig with the family of John A. McDonald and years afterward

Mrs. McDonald spoke fondly of him as "Charlie Schuchert" and remarked what a fine man he was. He was in Newfoundland and Labrador in 1910 with the writer as his assistant and together they walked from Flowers Cove to Forester Point, from Hawke Bay to Bell Burns Cove, and from Cow Head to Bonne Bay. He returned to Newfoundland in 1918 with Carl Dunbar as his assistant. The work was confined to the west coast and culminated in 1934 in the paper by Schuchert and Dunbar on the "Stratigraphy of Western Newfoundland."

Although his research in paleontology was largely focused on the Brachiopoda, it was not limited to this group of organisms as is shown by his memoir on "The Paleozoic Stelleroidea" in 1915.

The research which seems to have brought him most fame was in the field of paleogeography, not begun until after he came to Yale, yet foreshadowed in his paper with Doctor E. O. Ulrich on "Paleozoic Seas and Barriers" (1904). Many have considered paleogeography a field on the far frontier of extravagant speculation, but that this is not the case may be shown by the fact that Professor Schuchert's paleogeographic map in 1910 of the Pennsylvanian and early Permian showed an area of uplift in western Kansas long before the Central Kansas Uplift was known to the petroleum geologist. The writer does not know when Professor Schuchert first acquired the idea of paleogeography, but the research was going full speed when he first met him in September of 1907 and this research bore fruit on the publication of his" Paleogeography of North America" in 1910. This contained fifty maps and the necessary text. These maps have been revised again and again as new information developed and his third volume on the stratigraphy of North America, to be published when war restrictions are removed, will present his latest paleogeographic maps of North America.

His "Text Book on Historical Geology" has been the standard American text since publication of the first edition in 1915. The work is now in the fourth edition with the last two editions written in collaboration with Doctor Carl Owen Dunbar. The first volume of his last great work appeared in 1935. This treats of the stratigraphy of North America, the first volume giving the "Historical Geology of the Antillean-Caribbean Region." The second volume, treating of the "Stratigraphy of the Eastern and Central United States," appeared about the time of his death. The third volume, treating of the stratigraphy of Greater Acadia, eastern, central and arctic Canada, the Arctic Archipelago, and Greenland, will appear some time in the future.

He received the honorary degree of Master of Arts from Yale in 1904, the honorary degree of Doctor of Laws from New York University in 1914, the honorary degree of Doctor of Science from Yale in 1930, and the honorary degree of Doctor of Science from Harvard in 1935. He was president of the Geological Society of America in 1922 and Vice-President in 1910. He received the Penrose gold medal of the Geological Society of America in 1934, the Thompson gold medal of the National Academy of Sciences in 1934, and the Hayden gold medal of the American Philosophical Society in 1929. He was a member of many learned societies both at home and abroad. He was one of the founders of the Paleontological Society of America and its president in 1910. Three of his former students have also served as presidents of that society. Among American learned societies of which he was a member are the National Academy of Sciences, the Geological Society of America, the Paleontological Society of America, the Society of Economic Paleontologists and Mineralogists, the American Association of Petroleum Geologists, the Academy of Natural Science of Philadelphia, and the American Philosophical Society. He was an honorary corresponding member of the Academy of Sciences of Göttingen, the Society of Natural History of

Halle, the geological societies of Stockholm and Belgium, the Academy of Natural Sciences in Vienna, the National Academy of Norway, honorary foreign member of the Geological Society of London, the Royal Physiographic Society of Lund, and an honorary member of the Russian Paleontological Society and the Academia Asiatica of Persia.

Professor Schuchert was always a worshipper of heroes. Beecher and O. C. Marsh were to him two of the immortals. Eduard Suess, with his "Antlitz der Erde," was placed among the godly and he had steeped himself in the teachings and philosophy of Johannes Walther. O. C. Marsh was given a respect that was essentially reverential, Joseph Barrell's views were considered to have almost the validity of law, and his valued friend Russell H. Chittenden was frequently quoted as an authority. Charles D. Walcott and John M. Clarke were others whom he set apart.

He had few interests outside of his work. In his early days in New Haven, he met with three friends on one evening of each week for a game with cards. There was no gambling. In course of time these friends died so that in his later life there was little diversion except on the annual winter trip to Florida where he and his valued friend Russell H. Chittenden saw much of Florida together. Perhaps the event which gave Professor Schuchert as much pleasure as anything that was ever done for him was the occasion in 1938 on his 80th birthday when his portrait was presented to Peabody Museum by his former students. An address made by the writer on that occasion follows. It seems fitting to publish it in this connection.

"In the course of a life it falls to the lot of some to come in contact with a few people with the attributes of greatness—people by whom their lives are molded, bent from the groove of thought and action they have traveled, cast into new channels, from whom ideals are acquired that are different from those held before. One's life thus becomes like a stream swung from an older course by some cataclysmic act of Nature and forced to follow a new channel. This has happened in the case of some of the students who have worked with Professor Schuchert. It has some strange aspects so far as I am concerned. Professor Schuchert's physical path and mine had crossed without our knowing it. His birthplace and mine were less than three miles apart. I had wandered over the same hills in Ohio and Kentucky over which he had gone in earlier years. We both had the same goal—collection of the Ordovician fossils in which the rocks composing the hills abound.

"My first contact with the man whom we have assembled to honor came in the form of a letter from Yale to far away Texas. Professor Schuchert had been informed that there was a young fellow without a great deal of money living in Commerce, Texas, who was making a collection of fossils from the Lower Cretaceous of that region. The letter carried a request to make a collection of Lower Cretaceous fossils for Yale and there was enclosed a check for fifty dollars to pay for the work. The collection was made and the collector followed it to Yale. I was welcomed and more. Professor Schuchert even directed Mr. Bostwick, his assistant, to assist me in finding a place to live. At that time Schuchert was to me only a name among many, and not even a familiar name.

"The meeting was in the old Peabody Museum and it marked the beginning of a friendship which has held unbroken over nearly a third of a century. And that friendship is but one of many which Professor Schuchert has had with his students.

"At that time Professor Schuchert was delving deeply into North America geologic literature for data which would aid in unraveling the relations of ancient lands and seas. He had set for himself the task of deciphering the geology of North America of all time since the beginning of the Cambrian. When not in classes, he

could be found from early morning until late at night searching the literature and altering, or adding to the many maps on which he was attempting to depict the geography of the various geologic periods. These maps lay upon adjacent desks and daily the erasers removed and the pencils added to, or amended, the boundaries between the ancient lands and seas. It was my first contact with a great scientist at work.

"Nearly every day witnessed a conference between Schuchert and Barrell. Each carried his problems to the other and each tested out his ideas on the other. Each was a stimulus to the other, each reinforced the other's knowledge. The team work had gone on for years and it continued until fate, in 1918, willed that the daily conference should come no more.

In the year 1908–1909, I had the unique honor to be the only student in a course in paleontology taught by Professor Schuchert. I am glad to state that I recognized the privilege at the time. This course met twice each week in the basement of the old museum. It was scheduled to meet for one hour each day, but he stayed afterward for as long a time as I cared to ask questions. We talked on many things relating to paleontology, stratigraphy, evolution, and kindred subjects. Formality was laid aside and his personality came to the fore. That course of lectures revealed the man and showed that his heart was bent on advancing knowledge in his chosen and related fields to the ultimate limits.

"In 1908 be began with me the practice that he continued through succeeding years—that of sending advanced students into the field for the summer, often paying both expenses and salary from his own pocket. He was fifty years of age that summer and on July third of that year—his birthday—he was on Anticosti and sick. His diary contains an entry written on that day, which, in substance, is as follows—'I am fifty years of age today—twenty more years to study and do research.'

"For many years before his trip to Anticosti, Professor Schuchert had been deeply interested in the Paleozoic geology of the maritime province of Canada, and the lands surrounding the Gulf of St. Lawrence. His first visit to the region was in 1900, when in company with the late John M. Clarke he studied the section of the Silurian exposed at Arisaig, Nova Scotia, and the Devonian exposed around Gaspe. He made many visits in subsequent years and his students have described and studied nearly every important Paleozoic section exposed on the lands bordering the Gulf of St. Lawrence. Several of these students have made the geology of that region a field of major interest. No one has contributed so much to the solution of the geologic problems of that region as has been directly or indirectly done by Professor Schuchert. I was at Arisaig, in 1908, on Anticosti and the Mingan Islands in 1909 and I accompanied him to Newfoundland in 1910. M. Y. Williams was sent to Arisaig in 1910, and F. H. McLearn in 1914. Walter A. Bell worked out the Mississippian formations of the Horton-Windsor district in 1914. Carl Owen Dunbar accompanied Professor Schuchert to Newfoundland in 1918 and Dunbar returned there in 1920. Miss J. Doris Dart worked out the Silurian sequence in the Port Daniel and Black Cape areas on Chaleur Bay in 1923. G. Arthur Cooper was taken by Professor Schuchert to Percé in 1929 and in 1929 and 1930 G. W. Crickmay worked out the geology of the Matapedia Valley at the head of the Gaspe Peninsula. Lastly, in 1931, S. A. Northrop extended the study of the geology about Port Daniel and Black Cape on Chaleur Bay.

"Among teachers in great American Universities, Professor Schuchert has held an unique position. He was appointed to a professorship in Yale University without having acquired an academic degree, without having attended classes in any college, without having graduated from any high school, and he may be said to have accomplished the impossible, to have lifted himself by his own boot-

straps to the position to which he was appointed in 1904. Governing boards of great universities have not often made appointments of this character.

"Like all scientists—and may I add, like all men of worth—Professor Schuchert has had those with whom he did not agree. I know that he has been criticized at times with some degree of bitterness, but in all my association with him—now extending over nearly a third of a century—in his classes, in geologic meetings, in the field, in his home and in mine, and, in correspondence, I do not remember a single severe criticism or unkind word uttered against those who did not agree with him or against those who had criticized him. He, no doubt, had been deeply hurt at times—he would not be human if such were not the case—but he did not express his feelings to me.

"As a stimulus to students—at least to many of them—I have seen few to equal him. There seemed to be no limit to the problems he could suggest. When funds were wanting to support his students in their chosen work, he found means to give them support without permitting an appreciation that such was the case. And all too frequently it was his pocket-book that served as the bank from which the funds were drawn. This was generally done by giving the student something to do—work in the field in the form of making collections and working out stratigraphic sections or work in the library assembling data. I was the recipient of some of that support, and I am fully aware at this time that many of the data that I collected served him to little purpose. The collections made were studied by graduate students, generally the students who did the collecting, and in course of time they became the documentary paleontological treasures of Yale.

"Through his personal efforts, Professor Schuchert has assembled at Yale what is probably the largest and finest collection of brachiopods in the world. He began this collection when he was an amateur paleontologist in the Cincinnati region where on Saturday and Sunday, after the work of the week was over, he could be found wandering over the hills about the city with men of all walks of life. They were workers in offices, workers in breweries, doctors, ministers, lawyers and business men. Through personal collecting in many regions, exchange and purchase, the brachiopod collection has grown with the years. The work spent in assembling this great collection will pay dividends through the years to come and many students will be able to state that through it they were enabled to attain a broader knowledge of this group of organisms than would otherwise have been possible. With the assembling of the brachiopod collection has gone hand in hand the gathering of a great library on the literature of the brachiopods, each a fitting complement to the other.

"As the work of Professor Schuchert has progressed and his fame has grown, he has received an increasingly growing number of pamphlets and books in exchange for reprints of his own articles and as compliments to his attainments. These have gone to enrich the library of the museum. He has sought, in addition, to enlarge the library through purchase, often with his own funds, so that it is now one of the great libraries for study of paleontology and kindred fields of learning. And may I add, my own personal library owes many volumes to his generosity and I have little doubt but that other students of his may make a like statement.

"He became emeritus professor at the Yale Commencement of 1923 but continued to teach invertebrate paleontology until 1926 when he finally retired. Some years later a member of the staff of the Museum wrote me in substance that Professor Schuchert was working harder than ever, that he was the man on the staff best loved by the students, and that his influence over the graduate students was very strong even though he was not teaching. On the day in 1930, that he received the honorary degree of Doctor

of Science from Yale, Professor William Lyon Phelps in presenting him for the degree said in part: 'One of the most distinguished of the scientists of Yale, in the front rank of paleontologists . . . in 1904 appointed to Yale... becoming Professor Emeritus in 1923, since when he has, if possible, worked still harder. He may be seen at an early hour every morning entering the Peabody Museum. Although his professional interests are concerned with prehistoric time, he is held in the warmest affection by contemporary men; every one who knows him is his friend.' Retirement of Professor Schuchert meant release from administrative duties, release to do more work of the kind on which his heart was set. In the fifteen years since becoming Emeritus Professor he has published 75 papers, totalling 1190 pages, three editions of the 'Outlines of Historical Geology,' two editions of the 'Text-book of Historical Geology,' a 'Memoir on Orthoid and Pentameroid Brachiopods' with G. Arthur Cooper, 'Earth and Its Rhythms' and 'Brachiopoda' with Miss Clara Mae LeVene, and 'Historical Geology of the Antilean-Caribbean Region' (811 pages), and two more books are under way. And today, at the end of 80 years of active and productive life, he is as eager to attack new problems, to invade new fields, as in the days of long ago.

"My correspondence with Professor Schuchert makes an imposing file. The letters are full of sound advice. They are frequently long, they convey friendly criticism, they are written in such a way as not to antagonize, they always display a keen interest in advancement and progress. One piece of advice he gave me in substance is as follows, 'Attempt something big. Do a good piece of work every few years. But you must advance and your associates must know that you are advancing. So keep their interest keen and alive by publication of short articles from time to time in which you give the progress of your research.'

"The interests of Professor Schuchert's students have been Professor Schuchert's interests. And there are some who have worked with and under him to whom he has meant as much as a father.

"The portrait that his students and friends today present to Peabody Museum and Yale University shows Professor Schuchert in an attitude and mood which I am sure that his students cannot fail to recognize. It shows him in characteristic position at his desk. It shows the personal teacher, the kindly critic, the honest adviser, the loyal friend. He has his favorite organism, a brachiopod, in one hand, the companion of many years, a battered hand lens, ready for an examination, in the other, and back of him on the wall is a map showing the lands and seas as he had outlined them for late Cretaceous time.

"His career may be summed in these lines,—

O'er Ohio's hills he wandered,
Seeking ancient lore.
But the wider vision beckoned,
Opened wide the door.

He entered, scanned the ancient strata,
Made the fossils tell their story,
Marked the limits of the oceans,
Made the past relate its glory.

He sought for index fossils
By the shores of old Laurentia,
He sought for ancient shorelines
In Acadian Appalachia.

The only bounds to his travels
Were set by the gates of truth,
And with age his mind kept open
As in the days of youth.

Wide has been his influence
On scientific thought,
And his students carry onward
The lessons he has taught."

Professor Schuchert's bibliography, presented elsewhere by others, includes over 200 titles in addition to many memorials and reviews. The most note-

worthy of his memorials is his life of "O. C. Marsh: Pioneer in Paleontology" in collaboration with his secretary, Miss Clara Mae LeVene (1940). This work is even very interesting reading for the layman in geology and paleontology.

Professor Schuchert never married. He rarely referred to women and they seem to have had little interest for him. Intimations of a romance in his early years might have been inferred from remarks occasionally made by him, but in all the years which the writer has known him he may be said to have been wedded to his science. Certainly no one could have been more devoted to his love than he.

The ideas of many men become fixed by middle life and undergo little change in after years. Enthusiam may be present, but it is enthusiam for their work and the ideas born of their thinking of earlier years. Most nail their views to the masts of their ships and swear allegiance and loyalty to them. They are prepared to defend their views, the children of their thinking, to the ultimate limit. Not so Professor Schuchert. He examined the data, never failed to take a position. This position was immediately abandoned if new data required that it be so done. There was no thought of the consequences from abandoning a previous position. His philosophy in this respect may be summed in the lines from Longfellow—

> "New occasions teach new duties,
> Time makes ancient good uncouth.
> Let us then be up and doing,
> That we keep abreast of truth."

His enthusiasm for his work persisted until his last illness. His ability to change his views did likewise. He never attempted to defend the untenable.

His death has left a deep sense of loss in the hearts of his former students, to many of whom he was comparable to a loving father. He praised a work well done. He could and did criticize work not well done, but the criticism left few stings. He and Barrell were alike in this respect, both criticized as friends and left in the students a sense of gratefulness for what had been done.

Professor Schuchert was unquestionably "one of the great" of his time. No one could have dreamed in 1884, when Charles Schuchert watched his business reduced to smoke and ashes, that here was a man who almost sixty years later would be the most eminent paleogeographer of his day, a great paleontologist and stratigrapher, a most inspiring teacher, and a man revered by many former students.

I saw Professor Schuchert for the last time in Lakeland, Florida, at Christmas time in 1941. In response to inquiry, the clerk at his hotel stated that he was in his room. Requested to telephone, she stated that he could not hear the phone and that I should go up. I found him hard at work at a desk with piles of manuscript about him. He seemed in good health. We had dinner together. Last November I was advised that he was ill and that an operation was necessary. He died following the operation. He was buried in the old Grove Street Cemetery adjacent to the grave of one of his heroes, O. C. Marsh. He left his great brachiopod collection, his library, and much of his estate to Yale.

W. H. TWENHOFEL
Madison, Wisconsin

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 13, NO. 3, P. 130, DECEMBER, 1943

REVIEW OF PETROLEUM GEOLOGY IN 1942

F. M. VAN TUYL
Colorado School of Mines, Golden, Colorado

The Department of Publications of the Colorado School of Mines, Golden, announces the publication of the "Review of Petroleum Geology in 1942" as Volume 38, Number 3 of the *Quarterly of the Colorado School of Mines*. The "Review" is the work of Dr. F. M. Van Tuyl, head of the Department of Geology, with the cooperation of members of the staffs of the Departments of Geology, Geophysics, and Petroleum Engineering at the Colorado School of Mines.

The work comprises 75 pages and includes a list of 209 references to publications of the year. Included are noteworthy events and developments in the fields of geology, geophysics, geochemistry, geobiology, petroleum engineering and aerial photography.

The work was compiled through the cooperation of the Research Committee of the American Association of Petroleum Geologists and was presented in part at the 1943 annual convention of the Association at Fort Worth.

The editor of the *Quarterly* has announced that the review of the preceding year will be published annually as the April number of the *Quarterly*.

The present "Review" may be obtained from the Department of Publications, Colorado School of Mines, Golden, Colorado, at $1.00 postpaid.

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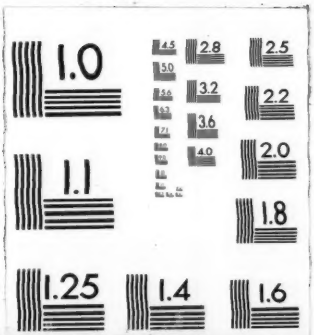
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